Radio Resource Sharing Games: Enabling QoS Support in Unlicensed Bands

Lars Berlemann, Guido R. Hiertz, and Bernhard H. Walke, RWTH Aachen University
Stefan Mangold, Swisscom Innovations

Abstract

Distributed quality of service support in wireless networks that are sharing unlicensed frequency bands is an increasingly significant research problem. The spectral coexistence of dissimilar radio systems has to be addressed in the near future in concerning the widely deployed IEEE 802.11 wireless local area networks and other future radio systems operating in unlicensed or opportunistically used frequency bands. The competition between independent wireless networks for allocating a common shared radio channel is modeled in this article as a stage-based game model: players, representing wireless networks, interact repeatedly in radio resource sharing games, without direct coordination or information exchange. Solution concepts derived from game theory allow the analysis of such models under the microeconomic aspects of welfare. Decisions players repeatedly have to make are about when and how often to attempt medium access. In multistage games the players apply strategies in order to maximize their observed utility as a summarizing value for successfully supported quality of service. Strategies determine whether competing radio networks cooperate or ignore the presence of other radio networks. The traffic requirements of a player thereby decide which strategy is adequate to guarantee quality of service.

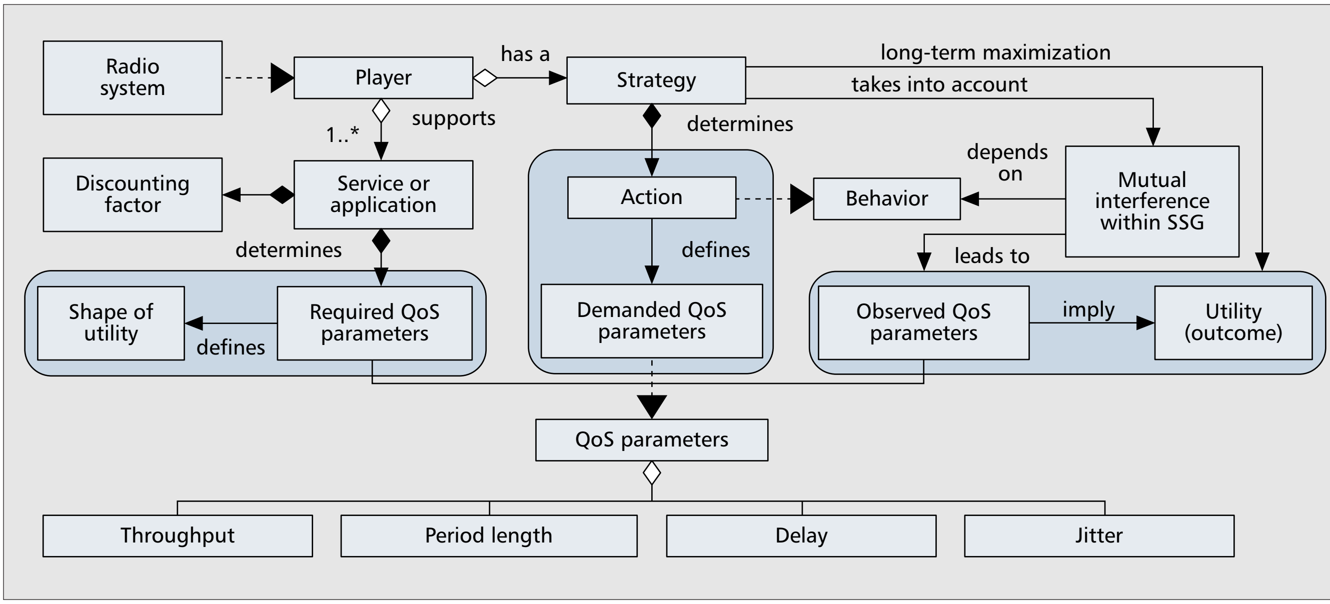
Wireless local area networks (WLANs) operate in unlicensed frequency bands. Their uncoordinated access to radio resources that are shared with other radio networks leads to increasingly problematic situations. Such coexistence scenarios are not addressed in standards like the popular IEEE 802.11 with its extension 802.11e for quality of service (QoS) support. For future radio networks, coexistence of dissimilar radio networks sharing common radio resources is under discussion in standardization groups like the Wi-Fi Alliance and IEEE 802.19. Wireless networks operating in unlicensed (i.e., open) spectrum are typically not designed to exchange information among dissimilar radio networks such as Wi-Fi and Bluetooth.

This article gives a tutorial description of using game theory for modeling the competition of WLANs sharing unlicensed frequency bands. Therefore, we approach the coexistence problem with a *stage-based noncooperative* game [1, 2] to analyze competition scenarios of two wireless networks. Fundamentals of game theory and its application in resource management for modeling the interaction between service provider and customers are introduced in [3]. Contrary to [4, 5], where cooperative relaying in ad hoc networks is considered, we focus on the decentralized coordination for distributed QoS support in unlicensed communication systems. The coexistence between broadband wireless access networks operating in unlicensed bands and WLANs (e.g., between WiMAX and Wi-Fi) can be another interesting application for our approach. The distributed coordination of reservations for spectrum allocation, as in wireless personal area networks (WPANs) as part of the Distributed Reservation Protocol (DRP) [6] in the Multiband OFDM Alliance (MBOA), is enabled as well.

Overview

To facilitate the understanding of the terms used in this article, we illustrate the concepts with the help of the Universal Modeling Language (UML) (Fig. 1). Each radio system is represented by a player that competes with another player for control over a shared resource to support QoS. Such a *player* stands for all medium access control (MAC) entities of one coexisting wireless network. In our example case of coexisting IEEE 802.11e WLANs, a player includes at least one 802.11e hybrid coordinator (HC). Although radio technologies for unlicensed bands share a common resource, they are typically not designed to arrange spectrum usage with different systems. We take this into account as we assume that players cannot establish communication with each other directly. The QoS *requirements* imposed by services and applications define a multidimensional utility function. The utility is an abstract representation of the observed throughput and delay. It is an important part of the stage-based game model and is discussed in detail later.

Players interact repeatedly by selecting their own behavior (= a selection of MAC parameters). For the sake of simplicity the behaviors of a player are limited here to cooperation and defection. After each stage of the game the players estimate their opponent's behavior. The estimated behavior of the opponent has to be classified in taking its intention into account, as discussed in detail later. This classification is nec-



■ Figure 1. *The game model in UML notation. A radio system is represented by a player, which has a strategy to determine what action to select. An action specifies a behavior. There are three QoS parameters: throughput, period length, and delay. The jitter can be derived from the delay.*

essary, as there is no communication between the dissimilar radio systems (i.e., the players), which hinders direct negotiations. Nevertheless, players are aware of their influence on the opponent's utility, which enables interaction on basis of punishment and cooperation, i.e., a handpicked allocation of the radio resource aiming at a specific intention.

The context of game theory for judging game outcomes is outlined on two levels. The existence of equilibria (i.e., steady outcomes of interaction) in single-stage games (SSGs) depends on the players' behaviors as outlined in one section. Strategies in a multistage game (MSG), which is formed by repeated SSGs, are then discussed as a second higher level. The players decide their strategy in discounting expected utilities to calculate future outcomes of the MSG. The selected strategy of a player is decisive for the course of interaction. Thus, the capability to guarantee QoS depending on the chosen strategy is evaluated.

The Single-Stage Game

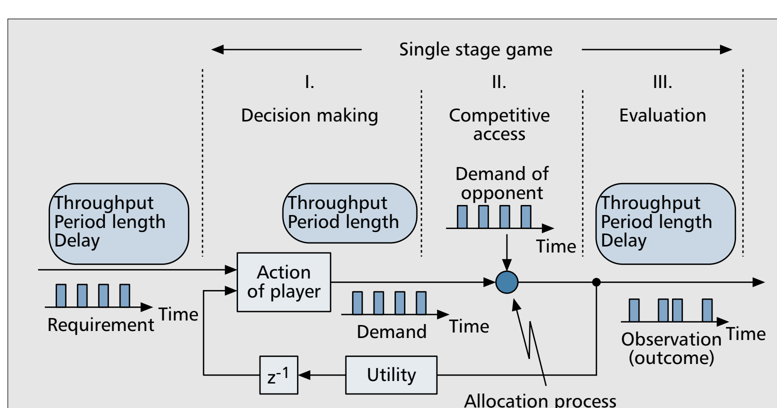
An SSG is formed by an IEEE 802.11e superframe and has a fixed time duration. Such a superframe is the time between two consecutive beacon frames that are used for broadcasts. These beacons can be used to determine such an interval, which in the following is arbitrarily set to a duration of 100 ms. Spectrum allocating players always allocate the shared channel exclusively with the help of the HC, whose allocations are referred to as transmission opportunities (TXOPs). Note that each player represents all MAC entities of a single coexisting WLAN, and each network is assumed to include at least one HC. During the SSG duration, the demanded resource allocation times of all players determine which individual player can allocate a TXOP at what time. An SSG consists of three phases, as illustrated in Fig. 2; together they form one single stage:

I. The players decide about their *action*, which means they *demand* resource allocation times and durations. This is an instant of time at the beginning of an SSG, and hence does not consume any time.

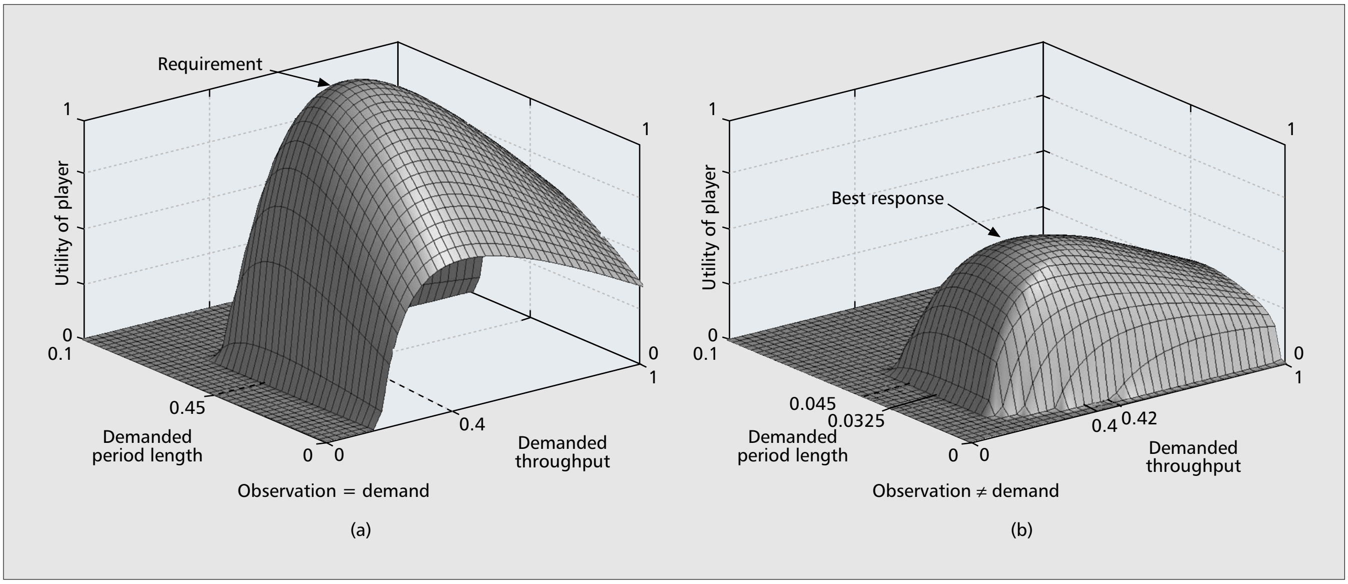
II. The competitive medium access of the allocation process during the SSG occurs in the second phase. It may result in resource allocation delays and collisions of allocation attempts: Resources may already be used by opponent players when an allocation attempt is demanded. Hence, the *observed* allocation points may differ from the demanded allocations, which are the reason for the difference between demand and observation. The second phase is the one that consumes the time of the SSG.

III. After the allocation process, players calculate the outcomes with the help of individually defined utility functions in the third phase of an SSG, again in an instant of time. The outcome can be regarded as the difference between what was wanted and what is de facto achieved.

Spectrum allocations can be observed by all players, but the observed utility of a player cannot be observed by opponent players. The utility (i.e., the outcome) is only individually known by each player. In the following stage, demands and actual observations are taken into account when the players decide which action to select next. Observed outcomes of an SSG contribute to the *game history* over multiple stages, as explained in more detail later.



■ Figure 2. *Repeated interaction on the basis of SSGs. An SSG consists of three phases.*



■ Figure 3. *Equally scaled utility functions of a player depending on its demanded throughput and period length: a) exclusive utilization: no opponent is present; b) under competition: the unlicensed radio resource is under competition and shared with an opponent.*

Quality of Service as Utility

We define three values between 0 and 1 that together represent the QoS targets for the players, as shown in Fig. 1 and Fig. 2: I) the throughput $\in [0,1]$, II) the period length $\in [0,0.1]$, and III) the delay $\in [0,0.1]$. Period lengths and delays are limited to grant typical values for a stage length of 100 ms. For a detailed definition of these QoS targets in the context of an SSG see [7]. The demanded throughputs and allocation intervals are determined by the player's demands. They are selected at the beginning of each stage. This selection is the actual decision making, or, as referred to in the rest of this article, the *action* of a player. The period length (i.e., interval between two successive TXOPs) aims at signaling the players' tolerable delay. The period length demanded by one player can be observed by opponent players, which is an important characteristic in our SSG to enable players to estimate their opponents' intentions and respond to their behaviors. With the help of the period length, a player can signal its own intention (e.g., cooperation); hence, this parameter allows the establishment of cooperation, as described in the next section.

Observed delay and throughput can be significantly different from the demanded parameters, because they result from the dynamics of the interactions during an SSG. This is reflected in the utility function. The multidimensional utility function represents the value of the observed QoS for a player. It is the unique objective of a player to optimize this value with respect to the utility function. The utility represents the supported QoS of a player and depends consequently on the above introduced three QoS targets. For example, an observed utility may be zero although the radio resource is not frequently used in times when a player is unable to allocate resources as required.

There are many different thinkable approaches to reflect QoS characteristics in a utility function. We have chosen an approach based on rational functions to simplify analytical analysis. Player i's utility U^i is defined as

$$U^i = U^i_{throughput} \cdot U^i_{periodlength} \cdot U^i_{delay},\ U^i \in [0\ldots1]. \quad (1)$$

The utility function U^i consists of three terms that are related to the throughput, period length, and delay.

For better understanding of the utility function, Fig. 3a depicts the observed utility of a player that exclusively utilizes the radio resource depending on its demanded QoS. As introduced above, the player can demand a specific throughput (i.e., share of capacity) and period length, together referred to as an action. The maximum of the utility function is per definition given by the required QoS: (*throughput*, *period length*, *maximum delay*) = (0.4, 0.045, 0.02). Missing this requirement implies either unfulfilled restrictions on the medium access or exceeding the actual needed resource utilization. Due to the exclusive resource allocation, the player observes this requirement when it is demanded and its allocations are not delayed. To force players not to allocate too much of the medium to the benefit of the opponent, the utility is reduced for high demanded throughputs. Furthermore, the utility function implies some kind of elasticity, whether a player may strictly need its requirement or is satisfied with less adequate observations. The dimensioning and definition of the utility function is described in [7].

Utility Under Competition

In a competition scenario of coexisting WLANs the radio resource has to be shared. Under such competition (i.e., in the presence of another player) the players' allocations interfere. Thus, the players observe lower QoS than demanded. This leads to decreased utility, as depicted in Fig. 3b. The opponent has a fixed QoS requirement of (*throughput*, *period length*, *maximum delay*) = (0.4, 0.02, 0.02), while the demanded throughput and period length of the player from above is varied. The observed delay, now inevitable because of the opponent's allocations of the shared radio resource, is considered in the utility function as factor 1, but is not part of an action. Furthermore, a player has to demand more restrictive QoS than needed to satisfy its QoS requirements. In this context, Fig. 3b illustrates the "best response" action of a player: the optimal pair of throughput and period length, here 0.42 and 0.0325. In a "best response" action, the resources demanded by the opponent are considered. Players estimate their opponent's demands [8], and use the history of interactions to predict the opponent's expected action for the next stage. This calculation results in an estimate for their expected potential utilities and thus determines the optimal best response.

Behaviors in Single-Stage Games

Cooperation through Predictable Behavior

In the absence of a centrally coordinating entity, a player can establish cooperation by behaving predictably. Predictable resource allocations of a player during an SSG enable other players to understand and respond to its actions.

For this reason, we refer to predictable behavior as a contribution to cooperation in the absence of a centrally coordinating entity [8]. The fixed periodicity of resource allocations by a player can be observed and predicted by other players. These other players may adapt their own resource allocations with the objective of mitigating mutual interference. Such behavior is cooperation in response to an opponent's cooperative behavior.

Actual resource allocations correspond to the individual QoS requirements of players. A decrease of the period lengths may, however, be considered another important contribution to establish cooperation [8]. While the number of equally distributed resource allocations per stage is increased, individual TXOPs (i.e., individual resource allocations) are relatively short, which can reduce the observed delays of resource allocations for opponent players.

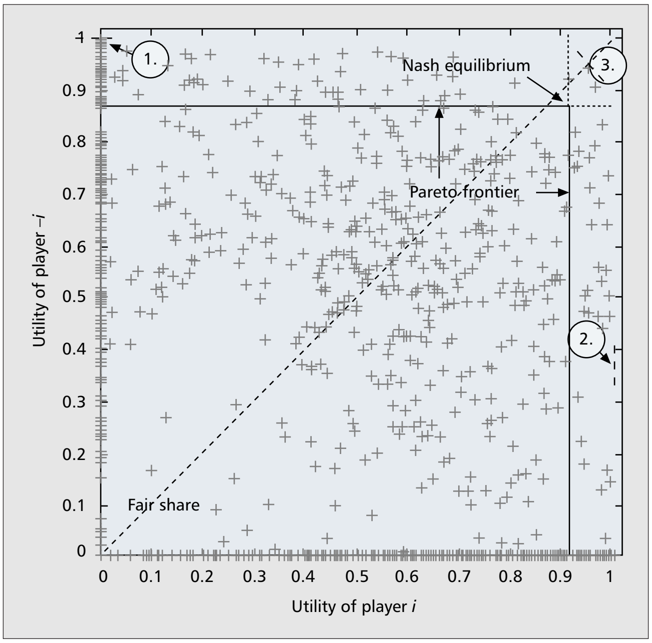
Classification of the Opponent's Behavior

Dynamic (trigger) strategies are used by players to change behaviors from stage to stage. They consider the strategies of opponent players. An opponent's strategy needs to be understood by a player that operates with such a dynamic strategy. Due to the lack of direct information exchange, it is impossible for a player to identify an opponent's strategy in the game model unless behaviors are altered by the opponent in an intelligent way. Players therefore have to classify the opponent's behavior by differentiating between two possible intentions: cooperation and defection. Players are aware of the influence of their demanded allocations on the opponent and vice versa. Consequently, they are able to identify a specific intended behavior. Cooperation (C) is defined as intending a behavior that aims for a fair share of resources. The second intention is defection (D), which can be motivated differently for two different reasons. The action that corresponds to defection is the known best response and is identical for the different motivations. On one hand, defection can be an intended act of ending established game-wide cooperation for the purpose of increasing the outcome. On the other hand, defection can be a reaction to an opponent's deviation from game-wide cooperation with the aim of punishing the opponent in response. Such a punishment can be implemented in different ways. All actions of a player that reduce the utility of the opponent can be considered *punishment*, because the player is aware of its influence on the opponent. To demand more restrictive QoS targets than needed, sending a busy tone or transmitting empty data packets are examples for punishing the opponent.

Defective behavior implies neglecting future payoffs motivated, for instance, by the players' support of applications on a best effort basis (e.g., email). Applications with restrictive QoS requirements (e.g., videoconferencing services) are one reason for cooperative behavior.

Equilibrium Analysis of a Single-Stage Game

The outcome of an SSG, the utility as defined above, depends on the observed QoS parameter. This can be determined by the players through an analytic model [8] based on the expected opponent action. It is interesting to analyze whether these outcomes from repeated simultaneous interactions are steady and/or utility maximizing. Therefore, in an SSG of rational acting players the existence of a best response action on the expected opponent action has to be considered. In addition, the uniqueness and stability of such an action is of interest for the players' decision-making on which action to take. A commonly used solution concept for the question of which action should be selected in an SSG of rational players is the Nash equilibrium (NE) solution concept [1, 2]. This solution concept in the context of our game model is outlined in the following.

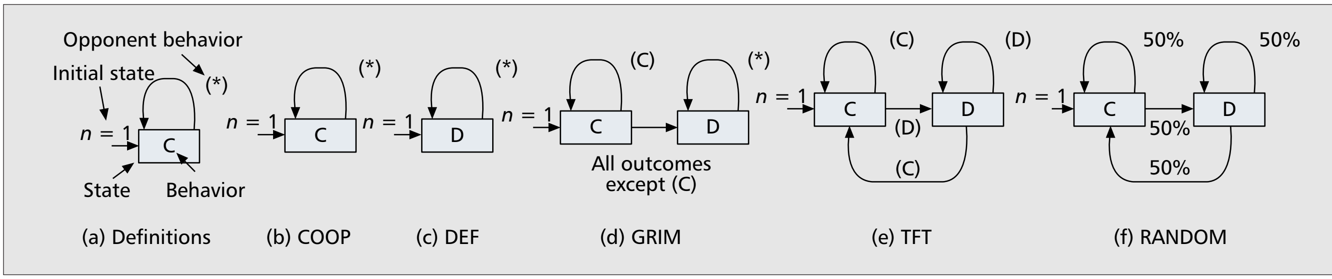


■ Figure 4. *The bargaining domain of a game scenario. Each cross marks the players' utilities of an SSG.*

In general, *"a NE is a profile of strategies such that each player's strategy is a best response to the other players' strategy"* [1]. Here, in the context of the SSG the players' strategy consists of a single specific action. This action leads to an observed utility as the outcome of the SSG. No player has the incentive to leave the NE, as a deviating action would imply a reduction of its own observed utility. Thus, NEs are consistent predictions of how the game will be played. In a sense, if all players predict that a particular NE will occur, no player has the incentive to play differently. Thus, an NE, and only an NE, can have the property that the players can predict it, predict that their opponents predict it, and so on. The NE is a value for the game's (in)stability. Hence, it can be seen as a lower limit for the QoS that can be guaranteed in a competition scenario of rational players.

A microeconomic concept to judge outcomes of a game is the *Pareto efficiency* [1]. An SSG outcome is called Pareto efficient if neither player can gain higher utility without decreasing the utility of at least one other player. A non-Pareto-efficient situation is not a preferable outcome of a stage because a rational player could improve its utility without changing the game and its outcome for the other player.

The *bargaining domain* of Fig. 4 contains a subset of all possible SSG outcomes by means of players' utilities corresponding to an action pair of players i and $-i$. Here, the actions belong to a discrete set. The corresponding SSG outcomes, utility pairs, are calculated with the help of an analytic model [8]. The bargaining domain supports the judgment of potential SSG outcomes. Depending on the players' QoS



■ Figure 5. *Static stratigies: a) Definitions of state machines for modeling strategies: b) cooperation; c) defection. Trigger strategies (dynamic strategies): d) the* GRIM *strategy defects forever, upon one opponent's defection; e) the TitForTat strategy defects after an opponent's defection and cooperates after an opponent's cooperation; f) the* RANDOM *strategy (f) implies a 50 percent chance of cooperation or defection.*

requirements, no NE, a unique NE, or several NEs can be found. Here we have game scenario of a unique NE with action player i demanding a throughput of 0.5 and a period length of 0.032, while the opponent $-i$ demands 0.54 and 0.03, respectively. The corresponding utilities are 0.913 and 0.872, as depicted in Fig. 4. This NE, which is not Pareto efficient, can be considered a minimum for the reachable utilities of both players. In this way a lower but nevertheless predictable limit for support of QoS is given. Further analysis indicates that this unique NE is reached as a steady outcome of an MSG if both players follow the best response behavior.

The single NE enables a definition of a *Pareto frontier*, which marks the reachable outcomes under a best response behavior. All outcomes outside the Pareto frontier are characterized by *Pareto domination* of the NE. The game scenario illustrated in Fig. 4 has three Pareto efficient outcomes: the utility pairs with maximum utility for each player located for player $-i$ in the upper left area of the bargaining domain (1) and for player i in the lower right area (2). The third Pareto efficient outcome is located in the upper right area (3) with the longest distance to the origin of the bargaining domain. There, contrary to the other two Pareto efficient outcomes, a both players gain higher utility than in the NE. As a result, both players can improve their utilities through interaction, compared to utilities in the NE. This interaction is referred to as cooperation to the benefit of all players and is the motivation for our focus on MSGs.

The Multistage Game

The above introduced SSG and behavior of a player allow us to introduce another degree of interaction: dynamic interaction in repeated SSGs, coordinated through strategies. Technical restrictions such as battery power limit the duration of an MSG. We nevertheless assume legitimately that MSGs have no limited time horizon: an MSG can be regarded as infinite as "*a model with infinite time horizon is appropriate if after each period the players believe that the game will continue for an additional period*" [2].

When selecting how to access the medium, players take into account the expected results (the expected utilities) of the instantaneous stage, but should also take into account the effects of their decisions on the utilities of future stages. This is usually expressed through weighting the stages. Players give present utilities a higher weight than potential utilities in the future, because of the uncertainty of those future results. A known approach to modeling this weighting of the future is to discount the utilities for each future stage of a game. Therefore, a discounting factor δ, $0 < \delta < 1$, is defined in [9]. δ reflects in the present stage the worth of future utilities of following stages. Player i's utilities U^i of an infinite MSG is defined as the sum over its utilities U_n^i of stage n discounted with δ^i:

$$U^i = \sum_{n=0}^{\infty} (\delta^i)^n U_n^i = \frac{1}{1-\delta^i} U_n^i, \text{ if } U_n^i = const. \tag{2}$$

A δ^i near one implies that future utilities are considered similar to the utility of the current stage. Thus, the player tends to cooperate to enable long-term high utility. On the contrary, a player with δ^i near zero only has its focus on the present utility and completely neglects potential future utilities, resulting in uncooperative defection [9].

Strategies in Multistage Games

In MSGs, strategies determine the behaviors for each individual SSG. Players try to optimize their utility by applying adequate strategies. Using a state model as defined in Fig. 5a, a strategy describes the alternatives of a player. Each state represents a certain behavior. A strategy also models under which circumstances a transition from one state to another happens; hence, it models decision making. We only allow what is in game theory referred to as a "pure" strategy [1]: Players have to choose one specific behavior for each stage, and cannot perform soft decisions by assigning probabilities to different state transitions. Strategies can be interpreted as social norms in repeated interaction: "*Social norms are isolated types of strategies that support in any game mutually desirable and thus stable utilities*" [2]. In other words, strategies enable QoS support independent from the opponent's strategy and QoS requirements. We distinguish in the following between static and dynamic (trigger) strategies.

Static Strategies

Static strategies are the continuous application of one behavior without regarding the opponent's strategy. In static strategies, there is no state transition, and the state model contains one single state. In our approach, the set of available static strategies is reduced to two. The cooperation strategy (COOP) is characterized through cooperating every time, independent of the opponent's influence on the player's utility. The COOP strategy is to the benefit of a player if the opponent cooperates as well. Figure 5b illustrates this simple strategy of following a cooperative (C) behavior. Equivalent to the COOP strategy, the defection strategy (DEF) consists of a permanently chosen behavior of defection (D). Figure 5c illustrates the DEF strategy as a state machine.

Dynamic (Trigger) Strategies Grim and TitForTat

Trigger strategies are well known in game theory [1, 2]. A trigger strategy is a dynamic strategy where the transition from one state to another is event-driven; an observed event triggers a behavior change of a player. Depending on the number of states (the number of behaviors a player may select), a large number of trigger strategies is possible. For the sake of simplicity, the familiar Grim (GRIM) and Tit-ForTat (TFT) trigger strategies are applied in the following. A player with a GRIM strategy punishes the opponent for a single deviation from cooperation with a defection forever. A player applying this strategy may be referred to as an unforgiving player. The initial state of the GRIM strategy, selected at the first stage of the MSG, is cooperation. The player cooperates as long as the opponent cooperates, and the transition to defection is triggered by the opponent's defection. See Fig. 5d for an illustration of the state machine of the GRIM strategy. The TFT strategy selects cooperation as long as the opponent is cooperating, similar to the GRIM strategy, also with cooperation in the initial stage. An opponent's defection in stage N triggers a state transition and is punished by defection in the following stage, $N+1$, as illustrated in Fig. 5e. However, in contrast to the GRIM strategy, TFT changes back as soon as the opponent cooperates again. The TFT strategy is well known in game theory and social science. The advantage of the TFT strategy is on one hand that it motivates opponent players to cooperate (because of the potential punishment), and on the other hand robustness when applied in noncooperative environments where opponent players often defect.

RANDOM Strategy

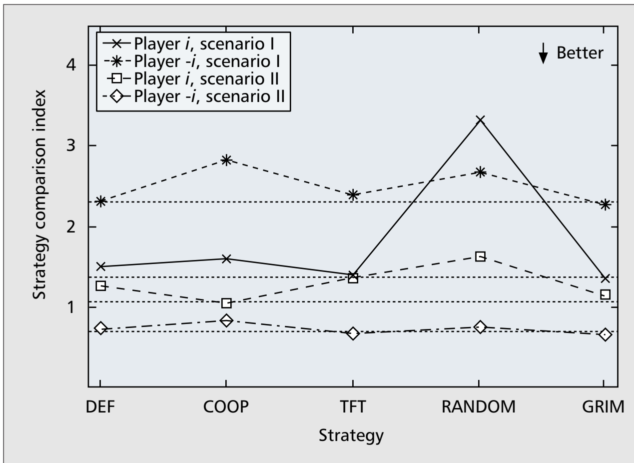
We also want to analyze how the different strategies perform when applied against purely random behavior. To analyze whether a random play or, alternatively, a deterministic predictable play that usually results in a stable course of the game is to the advantage of a player, we introduce the dynamic strategy RANDOM. This strategy, as shown in Fig. 5f, results in uniformly distributed behaviors, 50 percent cooperation (C) and 50 percent defection (D), regardless of which behavior the opponent player may select.

QoS Support in Multistage Games

MSGs can be evaluated based on the observed utilities to decide which strategy is optimal, as in [9]. This section continues this evaluation in considering the level of QoS support during an MSG. This reverses the abstraction done when introducing utility. Our game model and the basic IEEE 802.11e access mechanisms to a shared resource are evaluated with the help of our Matlab-based event-driven simulator YouShi [8].

The QoS capabilities of the strategies introduced in Fig. 5 are evaluated in the following. Multiple MSGs with varied strategies for both players are evaluated and summarized. Each strategy pair of players i and $-i$ has a corresponding course in the MSG. Such a strategy pair results in specific combinations of behaviors in the SSGs of an MSG. Such a behavior combination is noted as (behavior of player i, behavior of player $-i$), such as (C,C). The QoS outcomes in MSGs of various strategies are summarized in detail in [10]. The analyzed observed QoS of a player considers the achievable throughput, which is given as fraction of total capacity, as well as the probability of an observed TXOP allocation delay. The observed QoS of a player is evaluated over the outcomes of 400 stages of two-player MSGs. The players have normalized QoS requirements, introduced and defined in [8], of *(throughput, period length, maximum delay) = (0.4, 0.05, 0.02)* for player i and *(throughput, period length, maximum delay) = (0.4, 0.031, 0.02)* for player $-i$, referred to as game scenario I. A third participating player, not evaluated here, represents the background traffic and contention-based medium access.

For comparing the success of different strategies of a player, we need a summarizing value for each strategy. As the



■ Figure 6. *Strategy comparison of success in QoS support with the help of a strategy comparison index.*

opponent's strategy is unknown, we focus on the QoS values resulting from a strategy against the generality of all opponent strategies. Success against a specific single strategy of the opponent is therefore second rated. We define a weighted strategy comparison index (SCI) as a summarizing value for the capability of a strategy to support QoS [10]. The SCI contains the 98th percentile of the resource allocation delay (TXOP delay) distribution function together with the fulfillment of the required throughput of a player in applying the considered strategy against the opponent's strategy. We choose the strategies COOP, DEF, and RANDOM as representative of all available opponent strategies. The SCIs for both players resulting from MSGs are summarized in Fig. 6. Game scenario I leads thereby to the graph marked with crosses, and the other values are formed, respectively. The smallest SCI values indicate the strategy most adequate against all opponent strategies: the best strategy if the opponent's strategy is unknown to the player.

Corresponding to game scenario I, the GRIM strategy is the most adequate for both players to successfully support QoS. The best response behavior of the defection is adequate against a noncooperating opponent. Nevertheless, MSGs of game-wide cooperation for player i lead to shorter delays; thus, the GRIM strategy is the most suitable. This is contrary to the results of player $-i$, which show the same SCI value for the DEF strategy. The difference in the course of the MSG between the GRIM and DEF strategy is the behavior in case of a cooperating opponent. Game-wide cooperation (C,C) leads to shorter delays for player i than (D,C). This is not the case for player $-i$; thus, the DEF and GRIM strategies are both preferable. In summary, defective strategies are to be favored in this game scenario by both players.

Now, game scenario II with slightly different QoS requirements — for player i of *(throughput, period length, maximum delay) = (0.1, 0.05, 0.02)* and for player $-i$ of *(throughput, period length, maximum delay) = (0.4, 0.031, 0.02)* — is considered. The results are summarized in Fig. 6 with graphs marked by squares and diamonds. Here, the COOP strategy is the best for player i and the TFT strategy for player $-i$. As player i has a required throughput of 0.1, the competition for the medium is less severe than in the previous scenario, leading to an advantage in strategies with cooperative game outcomes of (C,C). Here, the best response optimizes the players' utility with less destructive interference (i.e., blocking of the medium) for the opponent: player $-i$, with a required throughput of 0.4, is more sensitive to the opponent's behavior and has a better QoS with the TFT trigger strategy.

Conclusion

The transfer of solution concepts from game theory and social science to the competition of radio resource sharing in wireless networks enriches our research with a new interdisciplinary aspect. Especially, the consideration of multiple QoS parameters in the players' coordination efforts are a decisive step toward a realization as extension of QoS supporting wireless communication protocols.

The application of game models enables aimed interaction and provides analysis of the competition for utilization of shared radio spectrum. Our analysis and simulation results indicate that cooperation is an achievable equilibrium that often improves the overall spectrum efficiency. Traffic requirements imposed by services and applications determine whether the selected strategies should pursue cooperation or ignore other radio systems, leading to games of defection. In such defective environments, a regulating intervention (e.g., specification of certain MAC parameters) would be advantageous to enable guaranteed QoS in all coexisting wireless networks. The learning in games to facilitate overcoming of insufficient information about opponents and game models of multiple players are the next steps to mitigate the mutual interference of radio resource sharing wireless networks.

Acknowledgments

The authors would like to thank the reviewers and editors for their constructive comments.

References

[1] D. Fudenberg and J. Tirole, *Game Theory*, MIT Press, 1998.

[2] M. J. Osborne and A. Rubinstein, *A Course in Game Theory*, MIT Press, 1994.

[3] S. K. Das, H. Lin, and M. Chatterjee, "An Econometric Model for Resource Management in Competitive Wireless Data Networks," *IEEE Network*, Dec. 2004, pp. 20–26.

[4] V. Srinivasan *et al.*, "Cooperation in Wireless Ad Hoc Networks," *Proc. INFOCOM 2003*, San Francisco, CA, 30 Mar.–3 Apr. 2003.

[5] E. Altman *et al.*, "Competitive Routing in Networks with Polynomial Costs," *IEEE Trans. Auto. Control*, vol. 47, Jan. 2002, pp. 92–96.

[6] G. R. Hiertz *et al.*, "A Decentralized Reservation Scheme for IEEE 802.11 Ad Hoc Networks," *Proc. PIMRC '03*, Beijing China, 7–11 Sept. 2003.

[7] S. Mangold, L. Berlemann, and B. Walke, "Equilibrium Analysis of Coexisting IEEE 802.11e Wireless LANs," *Proc. PIMRC '03*, Beijing China, 7–11 Sept. 2003.

[8] S. Mangold, "Analysis of IEEE 802.11e and Application of Game Models for Support of Quality-of-Service in Coexisting Wireless Networks," Ph.D. thesis, ComNets, RWTH Aachen Univ., 2003.

[9] L. Berlemann, B. Walke, and S. Mangold, "Behavior Based Strategies in Radio Resource Sharing Games," *Proc. PIMRC '04*, Barcelona Spain, 5–8 Sept. 2004.

[10] L. Berlemann, G. R. Hiertz, B. Walke and S. Mangold, "Strategies for Distributed QoS Support in Radio Spectrum Sharing," *Proc. ICC '05*, Seoul, Korea, 16–20 May 2005.

Biographies

LARS BERLEMANN [StM] (ber@comnets.rwth-aachen.de) received his Diploma degrees in electrical engineering and economics from RWTH Aachen University in 2002 and 2003, respectively. Since 2002 he serves as a research assistant with the Chair of Communication Networks (ComNets) at RWTH Aachen University, Germany, where he is working toward his Ph.D. degree. He holds the Research College (Graduiertenkolleg) Software for Mobile Communication Systems scholarship of the German Research Foundation (DFG). His current research interests include cognitive radios, distributed QoS support in spectrum sharing scenarios, spectrum etiquette, and flexible protocol stacks.

STEFAN MANGOLD [M] (stefan.mangold@swisscom.com) is a project leader at Swisscom Innovations Ltd., Bern, Switzerland, where he is working on cognitive radio, spectrum management, and IEEE 802 standards. Before joining Swisscom in April 2005, he worked at a research laboratory in the U.S. (2003–2005), and before that with ComNets at RWTH Aachen University, 1998–2003. He received his Diploma and Dr.-Ing. degrees (summa cum laude) in electrical engineering in 1997 and 2003, respectively, both from RWTH Aachen University. His current areas of research are operator=assisted cognitive radios for spectrum sharing and spectrum etiquette.

GUIDO R. HIERTZ [StM] (hiertz@ieee.org) received his Diploma degree in electrical engineering from RTWH Aachen University in 2002. After that he joined, as a research assistant, the ComNets at RWTH Aachen University, where he is working toward his Ph.D. degree. His research interests include QoS support in layer 2 protocols, IEEE 802.11, MBOA ultra wideband technology, and decentralized algorithms for wireless mesh WLANs and WPANs.

BERNHARD H. WALKE [M] (walke@comnets.rwth-aachen.de) is an internationally recognized expert (numerous publications, including several internationally published books) in the field of communication networks. His group's research work focuses on formal specification, modeling, mathematical and simulative analysis, and pilot implementation of protocols and services for communication networks. Having worked at AEG-TELEFUNKEN Research Institute and later at Fern University of Hagen (Chair for Data Processing Techniques), he has held the Chair of Communication Networks at RWTH Aachen University since 1990. He is a member of various national and international expert groups and coordination boards (e.g., ITG, AG Mobikom, WWRF) and has frequently served as an advisor to the German national regulation body (RegTP).