BEHAVIOR BASED STRATEGIES IN RADIO RESOURCE SHARING GAMES

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Abstract - Radio resource sharing among different, co-located wireless networks operating on the same frequencies is an unsolved problem when networks operate in unlicensed frequency bands. In this paper, we analyze such scenarios: in a stage-based game, wireless networks are modeled as players that attempt to meet individual quality of service requirements. Solution concepts derived from game theory allow the analysis of such models. Games are analyzed under the microeconomic aspects of welfare, constant requirements, evolving demands, and the resulting utilities (payoffs). A multi stage game consists of repeated stages, where each stage represents the interaction of competing wireless networks for a limited duration (the duration of a single stage). Throughout the course of repeated stages, players attempt to optimize their payoffs by changing behaviors. Each player follows a strategy to determine what behavior to select in a stage. Multi stage game Nash equilibria for optimized quality of service support are determined in this paper. Results indicate that, depending on the requirements, cooperation is an achievable equilibrium that improves the overall radio resource utilization.

Keywords - coexistence in unlicensed bands; cooperation and punishment; game models; multi stage games; quality of service as utility; dynamic strategies; IEEE 802.11e.

I. INTRODUCTION

Wireless Local Area Networks (WLANs) operate usually in unlicensed frequency bands, and consequently may often have to operate in problematic situations, where coexisting WLANs may severely interfere with each other. Such scenarios are not addressed in detail in existing radio standards like the popular IEEE 802.11(e) [1], [2]. We therefore approach this problem as a stage-based game [4], to analyze scenarios of two WLANs that share a common radio channel. We assume that the coverage area of the WLANs overlap entirely, and ignore the hidden station problem. Each WLAN is represented by a player, which interacts with another player (another WLAN), when competing for radio resources to support *Quality of Service (QoS)*. To address the fact that in unlicensed frequency bands, different wireless networks that are not able to exchange information may have to share radio resources, we assume that players cannot communicate directly. Interaction is therefore referring to selecting behaviors, and estimating the opponent's behaviors. This paper applies games to optimize throughput and delay with multi-dimensional utility and payoff functions. In the games neither player is aware of the demands and requirements of the respective opponent players. In the absence of any communication channel between the competing networks, player's cannot directly determine other players' preference of delay and jitter requirements through observation. However, a player can estimate the achieved throughput of opponent players, and to some extent derive delay and jitter requirements. We will describe the concept of demand and requirement in Section II.

A. Overview

Our analysis of *Single Stage Games (SSGs)*, summarized in Section II, indicates that all players can benefit from a dynamic interaction in repeated SSGs [9]. Hence, in this paper we focus on repeated SSGs, forming a *Multi Stage Game (MSG)*. Players estimate future expected outcomes of an MSG based on the discounted SSG payoffs. This is explained in detail in Section III: The expected outcomes of future stages are weighted with a discounting factor. The MSG outcomes depend on the players' strategy, which are differentiated in this work into static and dynamic trigger strategies. The existence of *Nash Equilibria (NEs)*, i.e. steady outcomes, within strategies is analyzed in Section IV. The underlying microeconomic concepts are introduced in detail in [9].

B. Related Work

This paper continues a row of publications, in which we discuss our approach of modeling the radio resource sharing of wireless networks as games [4], [8], [9], [10]. Contrary to [5], [6], where cooperative relaying in ad hoc networks is considered, this paper focuses on the support of QoS by means of cooperation in decentralized networks. Many publications concentrate on the cooperative optimization of a single QoS parameter, the throughput. For example, a channel-based optimization of the throughput is introduced in [7]: Optimal coding strategies, i.e. coding matrices, are provided to maximize jointly the information rate of a cooperating meshed wireless network of multiple, simultaneously active links. Other publications consider game approaches to coordinate power control or call admission control in a competition scenario. In our work, we focus on the coordinated medium access to a single, commonly used radio channel. Our approach with multi-dimensional utility functions allows a consideration of the delay as second parameter for QoS support. The delay is critical and should be taken into account, especially when

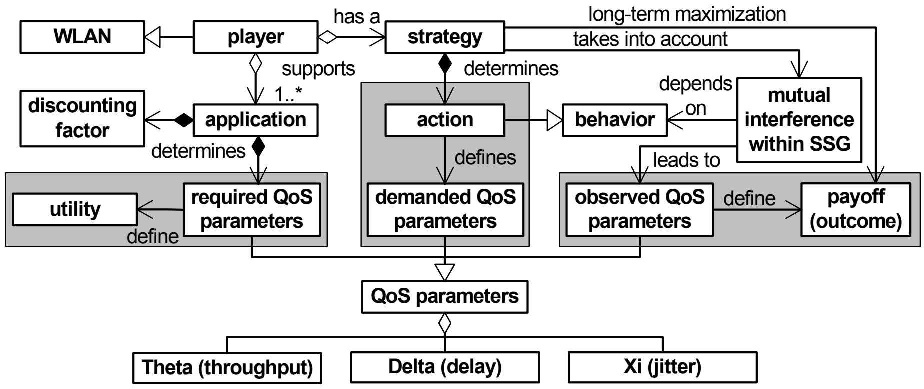


Fig. 1: [10] The game structure in UML notation. A WLAN is represented by a player, which "has a strategy", to determine what action to select. An "action specifies a behavior". There are three QoS parameters: Throughput, delay and jitter.

coexisting WLANs use the medium without coordination by a central instance. The jitter as third QoS parameter can be derived from the delay.

II. THE SINGLE STAGE GAME [10]

This section summarizes the game model of the SSG; for more details see Fig. 1 and [10]. An SSG is formed by a superframe [1] (a time interval with a typical duration of *100 ms* that begins with the transmission of a beacon, a broadcast management frame). Within a superframe, players attempt to allocate radio resources, i.e. they demand radio resources. The demand depends on the QoS requirements a player attempts to support. In times when players share resources with other players, the demand may differ from the requirement. For example, a player may simply demand more resources than required, for more reliable communication, and faster retransmission. The QoS requirements are reflected in individual *utility* functions for each player [9]. During the competitive access to shared radio resources, players' allocation attempts interfere (collide). The resulting QoS of an SSG is represented by the *payoff*, i.e. the observed utility under competition (often referred to as outcome). At the beginning of each single stage, players decide about their *action*. An action is the choice of demanded QoS parameters, which determines when resource allocations are attempted during the subsequent SSG. Each action and the resulting mutual interference with the opponent are a consequence from the player's *behaviors*: When players select behaviors, they take into account the expected resulting payoffs and the influence on the opponent's payoffs. Behaviors (actions) of players that reduce the payoff of the opponent are referred to as *defection* or *punishment*. Behaviors (and the resulting actions) that intend to improve a player's game outcome in the case of same behaving opponents are referred to as *cooperation*.

III. MULTI STAGE GAMES

The above-introduced game structure of an SSG, including the behavior of a player, allows us to introduce another degree of interaction: The dynamic interaction in repeated SSGs, coordinated by strategies. This potential interaction within MSGs is introduced and evaluated in the rest of the paper.

A. Game Structure

The structure of the MSG can be characterized as follows:

- The MSG consists of a finite number of stages, and the end of the MSG is unknown to players (which allows us modeling the game as infinitely repeated games),
- players maintain their own local information base about the status of the game: Information is non-symmetrically distributed among players,
- the actions are taken (behaviors are selected) at the beginning of each stage,
- there are no mixed strategies, hence, there is no probability distribution associated with the set of available behaviors: A player takes one single action at the beginning of each SSG,
- at each stage, players obtain a history H^t of observed outcomes of the past stages.

Technical restrictions, as for example the battery power of a mobile terminal, limit the duration of the MSG, hence there are no games with infinite duration. A finitely repeated game with known end is solved with backward induction: From the known end, the outcome of the last stage can be calculated. Based hereon the outcome of the previous stage and all other outcomes back to the beginning of the game are determinable. This backward induction is not possible in case the end of an MSG is unknown to the players. We assume that players do not know when the interaction ends, hence the MSG is a finitely repeated game with an unknown but existing end. Nevertheless, we assume that the MSG has no limited time horizon and regard the MSG as infinite, corresponding to that "*a model with infinite horizon is appropriate if after each period the players believe that the game will continue for an additional period"* [12]. Therefore, we are allowed to apply the same games as if the MSG would be infinite.

B. Discounting in Multi Stage Games

Players "*act rationally*" [12] when attempting to maximize long-term payoffs. Rational acting players give present payoffs a higher value than potential uncertain payoffs in the future. A known approach to model this preference is to discount the payoffs for each stage of a game. Therefore, a discounting factor λ, $0 < \lambda < 1$, is defined which reflects in the present stage the worth of future payoffs of following stages.

A λ near one implies that future payoffs have the same value as the payoff of the actual stage. Contrary, a player with a λ near zero only focuses on the present payoff and neglects potential future payoffs. The exact value of this discounting factor λ is determined by the applications that are supported by the player (as it is also the case for the shape of the utility function). It may be derived from the technical requirements of the QoS traffic types, as for example shown in Tab. 1 for the IEEE 802.11e protocols. Player *i*'s payoff V^i of an infinite game is defined as the sum over its payoffs V_t^i of stage *t* discounted with λ^i :

$$V^i = \sum_{t=0}^{\infty} \left(\lambda^i\right)^t V_t^i = \frac{1}{1-\lambda^i} V_t^i, \; if \; V_t^i = const. \qquad (1)$$

C. Strategies in Multi Stage Games

A *strategy* describes the alternatives a player has for an action under consideration of the repeated interaction of competing players. In our game structure the strategy of a player is the decision-making process about the own action. The game structure comprises pure strategies, contrary to mixed strategies. This means that a player has to choose one specific strategy and cannot play more than one strategy at the same time. Following Osborne and Rubinstein [12], strategies are steady social norms that support mutually desirable payoffs. We distinguish between static and dynamic (trigger) strategies, as explained in the following. Static strategies are based on a single behavior [9]. A static strategy is the continuous application of one behavior without regarding the opponent's strategy.

In contrast, dynamic (trigger) strategies consider the strategy of the opponent. The opponent's strategy has to be identified therefore by a player that selects a dynamic strategy. In our game structure it is impossible for the players to identify the opponent's strategy directly because the players are not able

Tab. 1: Discounting factors λ of different QoS traffic types based on IEEE 802.11e [2], derived from [3].

Traffic Type	802.11e Access Category	λ
Best Effort	0	0.25
Excellent Effort	1	0.5
"Video" < 100 ms latency, jitter	2	0.8
"Voice" < 10 ms latency, jitter	3	0.9

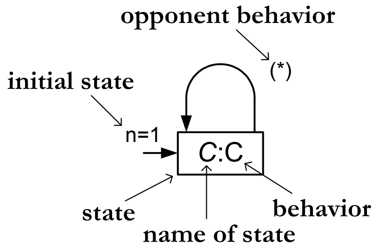


Fig. 2: Notation of Osborne and Rubinstein [12]. Strategies are modeled through state machines.

to exchange information about their strategies. Nevertheless, the players are able to classify the opponent's behavior, i.e. differentiate between two possible intentions, as introduced in the next section. Consequently, the player may react on the opponent's action in following a trigger strategy based on this classification. Trigger strategies lead in this way to simple interaction mechanisms: The opponent's behavior of the last stage triggers a specific action in the current stage determined through the player's trigger strategy. Strategies may be complex to describe. Therefore, [12] introduces the notation of state machines to describe strategies, as illustrated in Fig. 2. Especially trigger strategies, can be illustrated with the help of state machines. Each state has a specific name and a corresponding behavior. The initial state is marked, and the transitions to other states depend on the classification of the opponent's behavior.

1) Classifying the Opponent's Behavior

The classification of cooperation is defined as showing a behavior of 'Cooperation' as introduced in [9]. To identify the opponent's behavior 'Cooperation' as cooperation the players have to consider the game history H^t. The

Tab. 2: Common payoff table for an SSG of two players depending on their behavior.

Pl.*1*↓ Pl.*2*→	D	C
D	V_{DD}^1, V_{DD}^2	V_{DC}^1, V_{DC}^2
C	V_{CD}^1, V_{CD}^2	V_{CC}^1, V_{CC}^2

Tab. 3: Game scenario I. Simulated SSG payoffs. There is one NE (marked gray) as also illustrated in Fig. 3: (D|C), namely (0.71|0.31). Three outcomes are Pareto efficient, only (D|D) is not Pareto efficient.

Pl.1↓ Pl.2→	D	C
D	(0.25,0.05)	(0.71,0.31)
C	(0.24,0.78)	(0.40,0.56)

Tab. 4: Game scenario II - "Prisoners' Dilemma". The players' payoffs from SSGs are depicted. There exists one NE (marked gray): (D|D), namely (0.31|0.38). All outcomes are Pareto efficient except for this NE (D|D).

Pl.1↓ Pl.2→	D	C
D	(0.31,0.38)	(0.71,0.08)
C	(0.04,0.78)	(0.40,0.56)

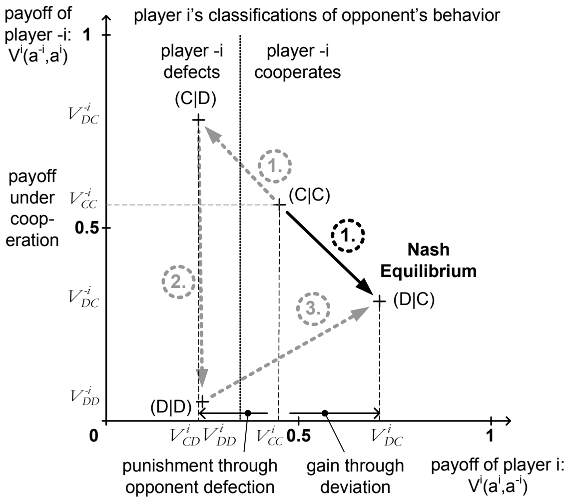


Fig. 3: Bargaining domain of game scenario I of Tab. 3. Originated in a game-wide cooperation, a unique NE is reached. Players know only their own payoff. The opponent's behavior is classified under consideration of the own payoff.

assumption that a cooperating opponent achieves a higher own payoff than an opponent, which is defecting, is combined with a MinMax evaluation of the observed payoff through own cooperation in the game history H^t. The players form an individual table of expected payoffs based on the common payoff table introduced in Tab. 2.

Defection has two motivations, although the action itself, the 'Best Response' action as introduced in [9], is identical: On the one hand it is the intended act of leaving an expected game-wide cooperation, while on the other hand it is the reaction on an opponent's deviation from game-wide cooperation with the aim of punishing the opponent in return.

Tab. 2 defines the payoffs of two players depending on the classification of cooperation (C) or defection (D). Player *1*'s cooperation/defection behavior is on the left column, player *2*'s in the upper row.

2) A Game of Coexisting IEEE 802.11e WLANs

The analytical results of this paper are evaluated with the help of our simulator YouShi [4]. YouShi models the basic 802.11e access mechanisms to a shared radio resource. A game scenario of two players, representing the controlled access (and contention) in overlapping WLANs operating at the same time and location, is defined with QoS requirements for throughput, delay and jitter as

$$\left(\begin{pmatrix}\Theta^1_{req}\\ \Delta^1_{req}\\ \Xi^1_{req}\end{pmatrix},\begin{pmatrix}\Theta^2_{req}\\ \Delta^2_{req}\\ \Xi^2_{req}\end{pmatrix}\right)=\left(\begin{pmatrix}0.4\\ 0.051\\ 0.02\end{pmatrix},\begin{pmatrix}0.4\\ 0.042\\ 0.02\end{pmatrix}\right). \qquad (2)$$

The values in the equation are examples leading to the payoffs of Tab. 3. A third player represents the low priority contention-based medium access of both WLANs, with an overall load of $5\ Mbit/s$.

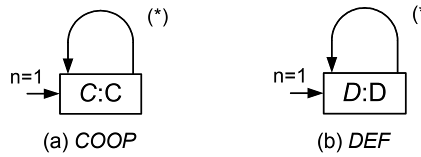


Fig. 4: State machines of static strategies cooperation (a) and defection (b).

To illustrate our first scenario, the scenario I, the bargaining domain, as comparison of the players' payoffs from an SSG, is shown in Fig. 3. Starting with a game-wide behavior of cooperation (C|C), both players have the incentive to deviate from cooperation to gain a higher payoff. In the case of player *-i* first leaving the cooperation (marked with "①" in the figure, gray dotted line) and deviating to (C|D), player *-i*'s payoff is increased, while player *i* observes a reduced payoff compared to the origin of (C|C). Consequently, player *i* decides to save (rescue) its payoff, and to punish the opponent in changing its behavior to defection (②). The resulting payoff reduction in (D|D) for player *-i* stimulates its return to cooperation (③). As player *i* has no incentive, i.e. an expected higher payoff, to leave (D|C), a stable point is reached. The same applies for the case of player *i* deviating as first from cooperation (①, solid line). Thus, in this specific game scenario, (D|C) is a stable point where neither player can gain a higher payoff: (D|C) is an NE.

3) Static Strategies

Static strategies are the continuous application of one behavior without regarding the opponent's strategy. In our approach, through the above-introduced classification of behaviors, the set of available static strategies is reduced to two, as explained in the following. The cooperation strategy (*COOP*) is characterized through cooperating every time, independently from the opponent's influence on the player's payoff. Fig. 4 (a) illustrates this simple strategy of following a cooperative behavior.

Equivalently to the *COOP* strategy, the defection strategy (*DEF*) consists of a permanently behavior of defection. The

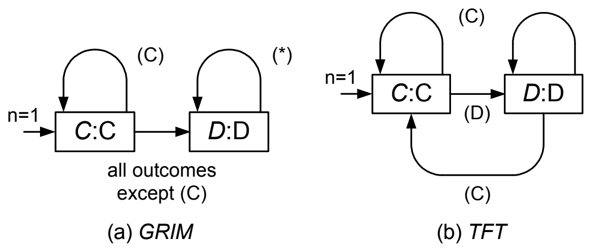


Fig. 5: State machines of trigger strategies (=dynamic strategies). The *GRIM* strategy (a) defects forever, upon one opponent's defection. The TitForTat (*TFT*) strategy (b) defects after opponent's defection, and cooperates after opponent's cooperation.

player maximizes its own payoff, independently from the opponent, while reducing the opponent's payoff. Fig. 4 (b) illustrates the *DEF* strategy as a state machine.

4) Dynamic (Trigger) Strategies GRIM and TitForTat

Trigger strategies have been analyzed for the first time by Friedman [13]. The well known Grim (*GRIM*) and TitForTat (*TFT*) trigger strategies are applied in the following. There are of course many more trigger strategies possible. A player with a *GRIM* strategy punishes the opponent for a single deviation from cooperation with a defection for the rest of the MSG. In this way the player is referred to as a "not forgiving player". The initial state of the *GRIM* strategy is the cooperation. The player cooperates as long as the opponent is cooperating. See Fig. 5 (a) for an illustration of the state machine of the *GRIM* strategy. The *TFT* strategy implies cooperation as long as the opponent is cooperating with cooperation in the initial stage. An opponent defection in stage *L* is punished by defection in stage *L+1,* as illustrated in Fig. 5 (b). The well-known TitForTat strategy by Rapoport was the winning strategy of a tournament of a *200* times repeated 'Prisoner's Dilemma' administrated by Axelrod [14]. The advantage of the *TFT* strategy is on the one hand the motivation for the opponent to cooperate because of a potential punishment and on the other hand the toughness against non-cooperative strategies.

IV. NASH EQUILIBRIA IN MULTI STAGE GAMES

To continuously guarantee QoS, even on a minimum but nevertheless predictable level, the players intend to establish a steady state, where behaviors do not change significantly, and future outcomes are predictable. Typically, the players attempt to influence this steady state to their advantage. The Nash equilibrium of an SSG implies 'Best Response' actions with satisfying outcomes and is the basis for the approach to a steady state in MSGs.

In extending the scope on multiple stages the level of potential interaction increases. The players have to consider future stages in their decision which action to choose for the actual stage. Therefore, static and dynamic trigger strategies are considered to improve the SSG outcomes in steady state. In this context the concept of the NE has to be extended to MSGs: Before we considered an NE for SSGs, now we need to find NEs for MSGs. The NE of an MSG is based on the players' strategies for the MSGs, as opposed to actions for the SSG. A pair of strategies is not a NE if any strategy can be found under whose application either player would gain a higher payoff. A strategy pair is an NE if no strategy can be found which is more preferable for any player. An NE of strategies in this paper corresponds to the classical understanding of an NE in game theory [11], [12].

A. Evaluation of Trigger Strategies

Trigger strategies may lead to higher payoffs for all players because they allow better mutual adaptation of behaviors. Therefore, the existence of NEs in such MSGs and the corresponding trigger strategies are analyzed in the following [15].

1) Multi Stage Games of the TitForTat Strategy

In this section the focus is on MSGs with two players in which (1.) both players prefer the TitForTat (*TFT*) strategy, and (2.) both players may seek incentives for alternative strategies. Player *i* prefers to switch from *TFT* to *DEF* if $V^i(DEF \mid TFT) > V^i(TFT \mid TFT)$, while player *-i* continues to apply the *TFT* strategy. In choosing the *DEF* strategy, player *i* gains a higher payoff V^i_{DC} at one stage, and in the subsequent stages, after player *-i* switches from cooperation to defection too, V^i_{DD} for the rest of the game. Thus the payoff inequality is solved, with discounting of Eq. (1) to

$$V^i_{DC} + V^i_{DD} \frac{\lambda^i}{1-\lambda^i} > V^i_{CC} \frac{1}{1-\lambda^i} . \tag{3}$$

In isolating λ^i , it can be derived that (*TFT*|*TFT*) results for

$$\lambda^i > \frac{V^i_{DC} - V^i_{CC}}{V^i_{DC} - V^i_{DD}} \tag{4}$$

in higher payoffs than (*DEF*|*TFT*). As illustrated in Fig. 3, the term $V^i_{DC} - V^i_{CC}$ can be regarded as the gain of player *i* from leaving the cooperation, while $V^i_{DC} - V^i_{DD}$ is the punishment that consequently follows the defection in *TFT* strategies.

We now define a *DEF1* strategy, which implies a single defection in stage *L,* and cooperation thereafter. The player has to compare the single deviation gain on the one hand to the consequently following punishment for one stage by the opponent with the *TFT* strategy in the subsequent stage on the other hand. Therefore, player *i* prefers to switch from *TFT* to *DEF1* if

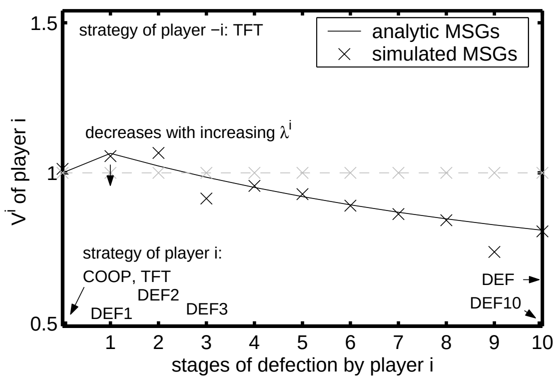
$$V^i_{DC}\left(\lambda^i\right)^L + V^i_{CD}\left(\lambda^i\right)^{L+1} > V^i_{CC}\left(\lambda^i\right)^L + V^i_{CC}\left(\lambda^i\right)^{L+1} . \tag{5}$$

Accordingly, (*TFT*|*TFT*) results higher payoffs compared to (*DEF1*|*TFT*) for

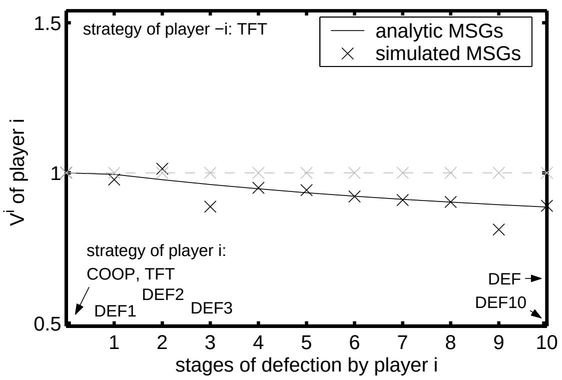
$$\lambda^i > \frac{V^i_{DC} - V^i_{CC}}{V^i_{CC} - V^i_{CD}} . \tag{6}$$

The term $V^i_{CC} - V^i_{CD}$ implies the payoff reduction for player *i* in case of an initial opponent deviation or an executed punishment as reaction. For λ^i of player *i* within the restriction of Eq. (4), (*TFT*|*TFT*) results higher payoffs than (*DEF*|*TFT*). Game scenario I of Tab. 3 leads for player *1* to a value of $\lambda^i \geq 0.690$. Eq. (6) restricts λ^i more: It leads in the same scenario to $\lambda^i \geq 2.05$. Consequently, there is no $0 < \lambda^i < 1$ for which player *1* would not prefer to switch to (*DEF1*|*TFT*). Contrary game scenario II of Tab. 4: Corresponding to Eq. (6) the player *1* would choose (*TFT*|*TFT*) for a $\lambda^i \geq 0.861$.

The strategies *DEF* and *DEF1* form a border for unlimited more strategies between these both. Based on our definition of an NE, the most restrictive value for λ^i is decisive for (*TFT*|*TFT*) being an NE. As the example illustrates, the strategy *DEF1* implies the highest temptation to defect and can be thus regarded in this way as lower limit for λ^i under which (*TFT*|*TFT*) is an NE.



(a) game scenario I



(b) game scenario II

Fig. 6: MSG outcomes of player *i*, with $\lambda^i = 0.9$, normalized to the payoff from a game of cooperation. The opponent has a *TFT* strategy. In (a) the strategies *DEF1* and *DEF2* are preferred while in (b) *TFT* and *COOP* dominate all other strategies. For increasing λ^i the payoffs from defection strategies are reduced due to the growing relevance of expected punishment.

Fig. 6 illustrates the results from above. The MSG outcomes V^i of player *i*, here player *1*, with the payoff tables from the game scenario I and II are depicted. The different strategies of player *i* imply a specific number of stages in which player *i* deviates from cooperation during an MSG. The opponent has a constant *TFT* strategy. The potential strength of punishment through the opponent, given by the specific game scenario, is decisive for player *i* which strategy to chose.

2) Multi Stage Games of the GRIM Strategy

We now focus on the *GRIM* strategy. Player *i*, playing against an opponent that also applies the *GRIM* strategy prefers to switch from *GRIM* to *DEF* if $V^i\left(DEF \mid GRIM\right) > V^i\left(GRIM \mid GRIM\right)$. In a game of (*GRIM|GRIM*) both players are cooperating during the complete game. In applying a *DEF* strategy, player *i* would gain in the first stage a deviation gain because player *-i* begins with cooperation. After the first stage player *-i* defects the rest of the game following its *GRIM* strategy and player *i* receives a reduced payoff because both players are defecting. The payoff equation is then given by

$$V_{DC}^i + V_{DD}^i \frac{\lambda^i}{1-\lambda^i} > V_{CC}^i \frac{1}{1-\lambda^i} . \tag{7}$$

Thus (*DEF|GRIM*) leads to a higher payoff than (*GRIM|GRIM*) for

$$\lambda^i > \frac{V_{DC}^i - V_{CC}^i}{V_{DC}^i - V_{DD}^i} \tag{8}$$

and is in this case an NE. It is the same restriction for λ^i as Eq. (4) resulting from the comparison of *DEF* and *TFT*.

3) Conclusion

The general existence of NEs in MSGs depends on the relation between the individual payoffs of each player and the possibility of the players to influence each other. Here the focus is on MSGs with a restriction of $V_{DC}^i - V_{DD}^i > V_{CC}^i - V_{CD}^i$. In other words, the payoff loss due to a defection of the opponent is smaller than the punishment through the opponent after an own defection. Hence, case Eq. (6) is more restrictive than Eq. (4) by means of

$$\frac{V_{DC}^i - V_{CC}^i}{V_{DC}^i - V_{DD}^i} < \frac{V_{DC}^i - V_{CC}^i}{V_{CC}^i - V_{CD}^i} . \tag{9}$$

In this way a lower limit for λ^i of player *i* is defined under which an NE from player *i*'s point of view is established. Furthermore is it easier to sustain a *GRIM* strategy pair as an NE than a *TFT* pair because of Eq. (9).

Note: The introduced NE analysis is independent of the players and has to be executed for players *1* and *2*, to find an NE of an MSG. This is shown in the next section.

4) Evaluation of Game Scenarios

Tab. 5 compares the strategies with the help of the payoffs from the game scenarios of Tab. 3 and 4. The outcomes of the MSGs, depending on the players' strategy, are calculated with the help of the discounted payoffs from (1). Analogous to the SSG the strategy pair of (*DEF|COOP*) is the unique NE of the MSG of scenario I (a) in the case of $\lambda^i = \lambda^{-i} = 0.9$. For higher discounting factors, satisfying Eq. (6) for both players, the strategy pair (*TFT|TFT*) would be the emerging NE as it is the case in scenario II (b). There, strategies which imply a game-wide cooperation lead to satisfying steady outcomes: The strategy pairs (*GRIM|GRIM*), (*GRIM|TFT*), (*TFT|GRIM*) and (*TFT|TFT*) are the Pareto efficient NEs of this MSG. Analogous to the SSG, the strategy pair of (*DEF|DEF*) is still a Pareto inefficient additional NE. In these two example game scenarios, the *GRIM* strategy dominates the *TFT* strategy: It leads always to equal or higher payoffs than *TFT*, as in these scenarios the punishment of the opponent implies simultaneously a significant increase of the own payoff.

V. SUMMARY AND CONCLUSION

Based on the behaviors of defection and cooperation, static and dynamic strategies can be defined in MSGs. A

Tab. 5: Discounted MSG payoffs depending on the players' strategy. The SSG payoffs are from Tab. 3 and 4. The payoffs are normalized to the MSG outcome of cooperation. The MSGs are played over *10* stages and both players have $\lambda^i = \lambda^{-i} = 0.9$. The NEs of the MSGs are marked gray. In (a) player *1* has no incentive to cooperate and the strategy pair (*DEF*|*COOP*) is the unique NE, while in (b) the strategies *TFT* and *GRIM* establish cooperation, contrary to (*DEF*|*DEF*).

(a) game scenario I

Pl.1↓ Pl.2→	COOP	DEF1	DEF	GRIM	TFT
COOP	1.00, 1.00	0.91, 1.09	0.60, 1.39	1.00, 1.00	1.00, 1.00
DEF1	1.17, 0.90	0.91, 0.80	0.61, 1.10	0.86, 1.20	1.10, 0.97
DEF	1.78, 0.55	1.52, 0.45	0.63, 0.09	0.88, 0.19	0.88, 0.19
GRIM	1.00, 1.00	1.51, 0.74	0.62, 0.38	1.00, 1.00	1.00, 1.00
TFT	1.00, 1.00	1.05, 1.01	0.62, 0.38	1.00, 1.00	1.00, 1.00

(b) game scenario II

Pl.1↓ Pl.2→	COOP	DEF1	DEF	GRIM	TFT
COOP	1.00, 1.00	0.86, 1.06	0.10, 1.39	1.00, 1.00	1.00, 1.00
DEF1	1.12, 0.87	0.96, 0.95	0.20, 1.28	0.36, 1.20	0.99, 0.92
DEF	1.78, 0.14	1.62, 0.23	0.78, 0.68	0.93, 0.60	0.93, 0.60
GRIM	1.00, 1.00	1.52, 0.33	0.67, 0.79	1.00, 1.00	1.00, 1.00
TFT	1.00, 1.00	0.97, 0.94	0.67, 0.79	1.00, 1.00	1.00, 1.00

discounting factor represents the players' preferences (assigned weights per future stage) of future payoffs. It enables a determination of reachable steady game outcomes as solution of the coexistence scenario. Depending on the QoS requirements and the resulting possibility of mutual interference, players decide about their strategy. Vulnerable players, which can be punished, may prefer dynamic trigger strategies, which imply typically a game-wide cooperation. An independence from future payoffs, i.e. less restrictive QoS requirements, typically means that players prefer to defect, and cooperation is then not a typical steady state outcome.

The discussed strategies indicate promising results for mitigating the addressed coexistence problem. The aspect of dynamic interaction is a step towards the successful support of QoS in a scenario where WLANs share radio resources. An analysis of the learning mechanisms within an MSG of adaptive strategies might lead to a further improvement of the decentralized coordination between the players.

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