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Radio Resource Sharing Model for Coexisting IEEE 802.11e Wireless LANs

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***Abstract*—A game model is developed and evaluated to analyze the Quality of Service (QoS) support in IEEE 802.11e Wireless Local Area Networks (WLANs) that share radio resources in a coexistence scenario. In such scenarios, QoS cannot be supported by the 802.11e Medium Access Control (MAC) protocol because of the unsolved competition between WLANs that operate in an unlicensed spectrum. A stage-based game model is introduced here in which WLANs are modeled as players. A player represents a Quality of Service Basic Service Set (QBSS). The interaction of the players within the Single Stage Game (SSG) is analytically modeled and evaluated with simulation.**

Keywords— Coexistence; IEEE 802.11e; QoS; Single Stage Game; Spectrum Sharing; Wireless LAN

ABBREVIATIONS

ACK	*Acknowledgement*
CF-Poll	*Contention Free – Poll*
EDCF	*Enhanced Distributed Coordination Function*
HC	*Hybrid Coordinator*
HCF	*Hybrid Coordination Function*
IEEE	*Institute of Electrical and Electronics Engineers*
MAC	*Medium Access Control*
MSDU	*MAC Service Data Unit*
MSG	*Multi Stage Game*
PIFS	*PCF Inter Frame Space*
(Q)BSS	*(QoS-supporting) Basic Service Set*
QoS	*Quality of Service*
RTS/CTS	*Request to Send/Clear to Send*
SIFS	*Short Inter Frame Space*
SFDUR	*Superframe Duration*
SSG	*Single Stage Game*
TBTT	*Target Beacon Transmission Time*
TXOP	*Transmission Opportunity*
TXOPlimit	*Maximum Length of an EDCF-TXOP*
WLAN	*Wireless Local Area Network*

I. INTRODUCTION

The IEEE 802.11 standard for WLANs [2] is currently under revision to enhance the existing MAC for support of QoS. The enhanced protocol is referred to as IEEE 802.11e [3], [4]. A group of communicating 802.11e devices is referred to as *QoS supporting Basic Service Set (QBSS)*. However, because WLANs mainly operate in unlicensed frequency bands, QBSSs may often have to operate in problematic situations, where coexisting QBSS have to share radio resources (often referred to as overlapping QBSS). Such scenarios are not addressed in detail in the enhanced standard. In this paper, a stage-based game structure is discussed [5], that helps to analyze scenarios where the competing QBSSs interact with each other for control over the used radio resources, i.e., for support of QoS.

An analytical model of the competitive access to shared radio resources is presented. Beginning with Section II, the limitations of 802.11e to support QoS are summarized. To support nevertheless QoS, a model of *Single Stage Games (SSGs)*, founded on 802.11e superframes, is presented in Section III. Section IV introduces a Markov model as an analytical approximation of this SSG. In Section V, a comparison of the approximation to simulation results is presented. The paper concludes with a summary in Section VI.

II. GUARANTEE OF QOS IN OVERLAPPING WIRELESS NETWORKS

Here we briefly introduce some aspects of the 802.11e MAC protocol which is currently being defined by IEEE 802.11 Task Group E. In addition an overview of the coexistence problem of overlapping QBSS is given under consideration of the possibility to guarantee QoS. In the following we assume fully overlapping QBSS coordinated each by a *Hybrid Coordination Function (HCF)*. QoS can be guaranteed in an isolated QBSS through the exclusive right of the centrally coordinating *Hybrid Coordinator (HC)*, to access the medium with highest priority.

The distributed medium access based on the *Enhanced Distributed Coordination Function (EDCF)* is operating in parallel: The EDCF gains a *Transmission Opportunity (TXOP)* through the well known listen-before talk medium access. Fig. 1 depicts exemplary single transmissions of HC *1* and HC *2* that are delayed by an EDCF-TXOP.

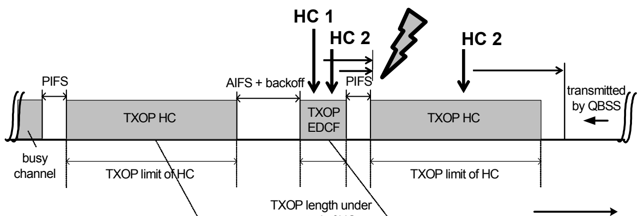

Fig. 1: Scenario of overlapping QBSSs. During an ongoing EDCF transmission the poll attempts of HC *1* and HC *2* are delayed. Due to the lost exclusiveness, the following polls of both HCs collide. Further on an allocation attempt of HC *2* during a HC TXOP is depicted, which is not under control of HC *2*. Consequently no guarantee of QoS can be given.

In a scenario of two overlapping QBSS, QoS cannot be guaranteed by the HCs. The presence of another HC eliminates the exclusive right to access the channel. In addition the maximum durations of EDCF-TXOPs are out of the HC's control. An access to the channel for one HC during a TXOP transmission of another HC may be delayed significantly. On the right side of Fig. 1 the poll attempt of HC *2* is delayed by an ongoing HC transmission. This delay can neither be limited nor be predicted by the HC *2*. Thus HC *2* is unable to guarantee QoS.

Because of the lost exclusiveness, poll frames may collide after an ongoing EDCF-TXOP: if during an EDCF transmission both HCs have the necessity for a poll, the HCs both wait until the channel gets idle again. After the EDCF-TXOP ends, both HCs initiate to transmit their poll after waiting a short duration (called PIFS in 802.11e). Fig. 1 illustrates such a collision of HC *1* and HC *2* after an ongoing EDCF transmission. An upper limit for the potential delay can not be specified. The collision resolution is not part of the IEEE 802.11e standard [3], as it should be implementation dependent.

III. COEXISTENCE GAME MODEL

A game model comprises a set of decision making entities called players, which choose their actions in each stage of the game. Each player represents an independent QBSS. Repeated SSGs form a *Multi Stage Game (MSG)*. In the following, a RTS/CTS/DATA/ACK sequence of 802.11e frames initiated by a HCF is summarized as a single TXOP.

A. QoS Parameters of a Player

The QoS parameters we are looking at are throughput, TXOP delay, and delay variation. The player's QoS demands are taken from the traffic specifications of the streams that are currently carried within the QBSS. We assume that the demands change slowly in comparison to the speed of the game, i.e. the decision-taking. We define three abstract and normalized representations of the QoS parameters: (1) the throughput Θ, (2) the delay Δ and (3) the delay variation Ξ. The delay variation is in the following not considered.

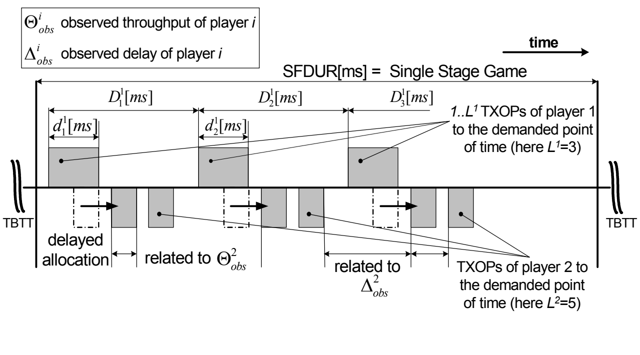

Fig. 2: Two players are in competition to access the radio channel. Exemplary for player *1* the figure intruduces d^i , D^i and L^i . Further it shows the relation between the players' allocations and their observed QoS parameters Θ^i_{obs} and Δ^i_{obs} , here depicted for player *2*.

1) Definition of the Allocation Parameters

The parameters d^i_l, D^i_l, L^i_l define the allocation l of player *i*. They are exemplarily depicted for player *1* in Fig. 2. These parameters depend on a specific action, i.e. on the demanded QoS parameters:

$$\begin{aligned} L^i &= \left\lceil \frac{1}{\Delta^i_{dem}} \right\rceil, \quad \Delta^i_{dem} > 0; \\ D^i &= SFDUR \cdot \Delta^i_{dem}; \\ d^i &= SFDUR \cdot \Theta^i_{dem} \cdot \Delta^i_{dem}. \end{aligned} \tag{3.1}$$

The operator $\lceil \cdot \rceil$ rounds to the nearest integer value toward plus infinity, and is neglected in the following.

2) Different QoS Parameters

Each player *i* knows three different QoS parameters: the "required" (*req*), "demanded" (*dem*) and "observed" (*obs*) QoS parameters. Fig. 3 illustrates the interdependencies of these parameters in the context of a repeated SSG.

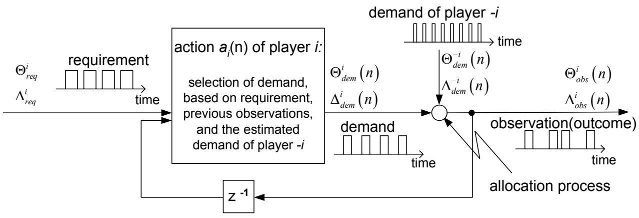

Fig. 3: The different QoS parameters of player *i* in an SSG. The requirement is defined by the QoS a player attempts to support. Concerning this requirement, a player chooses its demand, i.e. action. This demand is reduced through the competition in the allocation process to the observation.

Player *i*'s required QoS parameters Θ^i_{req} and Δ^i_{req} are defined through the QoS traffic which the player is trying to support. Before each SSG the players decide about their demanded allocations, i.e. actions, leading to the demanded QoS parameters Θ^i_{dem} and Δ^i_{dem}. They are changed by the player from stage to stage and determine the allocation points of time and lengths of TXOPs within a superframe. In general, a player observes less and delayed TXOPs through the allocation process. This leads to the observed QoS parameters Θ^i_{obs} and Δ^i_{obs}.

IV. ANALYTIC MODEL OF THE SINGLE STAGE GAME

Before the actual play of an SSG, players must take their actions for that particular stage. This is performed by player *i* based on its own QoS requirements that are given by Θ^i_{req} , Δ^i_{req} , with the consideration of the opponent player's demands $\widetilde{\Theta}^{-i}_{dem}$, $\widetilde{\Delta}^{-i}_{dem}$. The index *-i* refers to the opponent of a player *i*. Note, that the superscript "~" indicates the fact that the demands of any opponent player *-i* are not known to a player *i*, but estimated from the history of earlier stages of repeated SSGs.

In this section, a model for the game of two players that allows an analytical approximation of the expected observations as functions of the demands is presented. The approximation is calculated by means of a Markov chain with five states. Note that in the rest of this paper, the dependency of some game parameters on the game stage n is not indicated, since it is the SSG that is analyzed here.

A. Illustration and Transition Probabilities

In an SSG of two players, the calculation of the QoS observations is performed using the discrete-time Markov chain P illustrated in Fig. 4 and defined by Equation (4.1). The longer the duration of an SSG and the higher the number of allocation attempts per stage, the more stationary the process becomes. A minimum of 10 resource allocations per player is required, i.e. $\Delta_{dem}^{i,-i} < 0.1$, thus, stationary of the SSG is approximatively achieved.

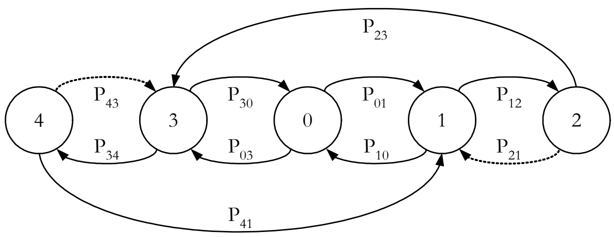

Fig. 4: Discrete-time Markov chain P with five states to model the game of two players that attempt to allocate common resources. The default state in which the channel is idle or an EDCF frame exchange is ongoing is denoted as state 0.

Table 1: The five states of the Markov chain.

State	Description
0	The channel is idle or allocated by low priority EDCF-TXOPs.
1	Player 1 successfully allocates resources with highest priority. Player 2 does not attempt to allocate resources.
2	Player 1 successfully allocates resources with highest priority, player 2 waits for the channel to become idle.
3	Player 2 successfully allocates resources with highest priority. This state is equivalent to state p_1 that models the same situation for the opponent player 1.
4	Player 2 successfully allocates resources with highest priority, player 1 waits for the channel to get idle.

Further, it is assumed that none of the states is periodic. The aperiodic characteristic of P is a necessary condition for the game analysis, and cannot be assumed in general.

With $P_{03}=1\text{-}P_{01}$, $P_{10}=1\text{-}P_{12}$ and $P_{30}=1\text{-}P_{34}$, and by approximating $P_{21}\rightarrow 0$ and $P_{43}\rightarrow 0$, the corresponding transition probability matrix is denoted with

$$P=\begin{bmatrix} 0 & P_{01} & 0 & 1-P_{01} & 0 \\ 1-P_{12} & 0 & P_{12} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 1-P_{34} & 0 & 0 & 0 & P_{34} \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \qquad (4.1)$$

The five states the SSG process, which is modeled by P, can be in are introduced in Table 1. The resulting transition probabilities with $P_{ki} \geq 0,\ i,\ k=0\ldots 4$ are presented in Table 2.

Table 2: The transition probabilities with $P_{ki} \geq 0,\ i,\ k=0\ldots 4$.

Trans. Prob.	Description
P_{01}	Probability that player 1 allocates resources while the channel is idle or allocated by low priority EDCF-TXOPs.
P_{03}	Probability that player 2 allocates resources while the channel is idle or allocated by low priority EDCF-TXOPs that allocate resources via contention. $P_{03}=1\text{-}\ P_{01}$.
P_{10}	Probability that player 2 does not attempt to allocate resources during an ongoing resource allocation of player 1.
P_{12}	Probability that player 2 attempts allocating resources during an ongoing resource allocation of player 1, $P_{12}=1\text{-}P_{10}$.
P_{21}	Probability that player 2 gives up its attempt to allocate resources before player 1 finishes its resource allocation.
P_{23}	Probability that player 2 allocates resources right after player 1 finished its resource allocation.
P_{30}	Probability that player 1 does not attempt to allocate resources during resource allocation of player 2.
P_{34}	Probability that player 1 does attempt to allocate resources during resource allocation of player 2, thus, $P_{34}=1\text{-}\ P_{30}$.
P_{41}	Probability that player 1 gives up its attempt to allocate resources before player 2 finishes its resource allocation.
P_{43}	Probability that player 1 allocates resources right after player 2 finished its resource allocation.

B. Solution of the Markov Chain P

The stationary distributions of the Markov chain P can be calculated to

$$\begin{aligned} p_0 &= 1-p_1-p_2-p_3-p_4\ , \\ p_1 &= \frac{1}{2}\cdot\frac{P_{34}+P_{01}\cdot(1-P_{34})}{1+P_{34}+P_{01}\cdot(P_{12}-P_{34})}\ , \\ p_2 &= P_{12}\cdot p_1\ , \\ p_3 &= \frac{1}{2}\cdot\frac{P_{12}+(1-P_{01})\cdot(1-P_{12})}{1+P_{12}+(1-P_{01})\cdot(P_{34}-P_{12})}\ , \\ p_4 &= P_{34}\cdot p_3\ . \end{aligned}$$

Here, we assume $P_{23}\rightarrow 1$ and $P_{41}\rightarrow 1$ to address that players tolerate delays of their resource allocation attempts, which occur when the opponent player allocates resources. It is assumed that a player never gives up its attempt to allocate resources when this player waits for the opponent player to finish its resource allocation. This implies the simplification that a player does not attempt to allocate more than one resource during one single ongoing resource allocation by the opponent player.

C. Transition Probabilities Expressed with QoS Demands

In this section, the QoS demands are used to determine the transition probabilities of P. The transition probability that player 1 allocates resources while the channel is idle or allocated by low priority EDCF-TXOPs via contention is approximated as

$$P_{01} \simeq \frac{L^1}{L^1+L^2},\quad L^1, L^2 > 0\ . \qquad (4.2)$$

During an SSG, the more TXOPs, L^1, player *1* attempts to allocate compared to the number of all high priority TXOPs, L^1+L^2, the higher the probability of resource allocation of this player *1*. With $P_{03}=1\text{-}P_{01}$, the probability of resource allocation of player *2* can be calculated similarly.

It is further approximated that the transition probability for player *2(1)* attempting to allocate resources during an ongoing allocation of player *1(2)*, is given by

$$P_{12(34)} \simeq min\left(1, \frac{d^{1(2)}}{D^{2(1)} - d^{2(1)}}\right). \tag{4.3}$$

These transition probabilities are declared in a piecewise way. The probability P_{12} is either $d^1 / D^2 - d^2$ or approximated to *1*, as expressed by Equation (4.3). The probability that player *1* decides to attempt a resource allocation while player *2* is allocating resources, depends on the ratio between the duration of this allocation d^1 and the duration of the time interval between two consecutive demanded resource allocations of player *2*, i.e., $D^2 - d^2$. In the case that the time interval between two consecutive demanded resource allocations of player *2*, given by $D^2 - d^2$, is smaller than the duration d^1 of a resource allocation by player *1*, the player *2* will attempt to allocate resources immediately after the ongoing resource allocation, with probability *1*. For the reverse situation P_{34} is equivalently defined.

With the QoS demands as given in Equation (3.1), the transition probabilities of *P* are

$$P_{01} = \frac{\Delta^2_{dem}}{\Delta^2_{dem} + \Delta^1_{dem}}, \quad \Delta^{1,2}_{dem} > 0,$$

$$P_{12(34)} = min\left(1, \frac{\Delta^{1(2)}_{dem}}{\Delta^{2(1)}_{dem}} \cdot \frac{\Theta^{1(2)}_{dem}}{1-\Theta^{2(1)}_{dem}}\right), \quad \Delta^{2(1)}_{dem} > 0, \Theta^{2(1)}_{dem} < 1,$$

with $0 \le P_{01}, P_{12}, P_{34} \le 1$.

D. Average State Durations Expressed with QoS Demands

The average state durations T_0, T_1, T_2, T_3, T_4 are further required to calculate the QoS observations from the stationary distributions of *P*. The average duration of the model *P* being in the idle state, T_0, is approximated to

$$\begin{aligned} T_0 &\simeq min\left(D^2 - d^2, D^1 - d^1\right) = \\ &SFDUR \cdot min\left(\Delta^1_{dem} \cdot \left(1\text{-}\Theta^1_{dem}\right), \Delta^2_{dem} \cdot \left(1\text{-}\Theta^2_{dem}\right)\right) \end{aligned}, \tag{4.4}$$

with the help of the QoS demands from Equation (3.1). This is understood as follows. If both players attempt to allocate resources periodically, the idle times between the resource allocations of a player *i* is denoted as $D^i - d^i$. In general, the player that requires shorter periods determines the average T_0 of the SSG. This is represented by the first part of Equation (4.4). The value of T_0 can be simplified to $T_0 \rightarrow 0$ for situations where the overall throughput demands of all involved players are relatively high, i.e., $\sum_i \Theta^i_{dem} \rightarrow 1$. In this case, it is very probable that the contention-based channel access through EDCF cannot allocate any resources due to its low priority in medium access. Therefore, if $\sum_i \Theta^i_{dem} \rightarrow 1$, resources are nearly always allocated by one of the two players; the channel is busy most of the time.

The mean state duration is given by

$$T_{Mean} \simeq p_0 T_0 + p_1 \cdot d^1 + p_3 \cdot d^2$$

because the duration of the process *P* being in state p_1 is determined by the duration of a resource allocation of player *1*, d^1, if the opponent player *2* does not decide to attempt resources during this allocation. In addition, if the opponent player decides to attempt a resource allocation during this allocation, the process changes to state p_2. The duration of the process *P* consecutively being in the states p_1 and p_2 is again determined by the duration of a resource allocation of player *1*, d^1. Therefore, it can be approximated that

$$p_1 T_1 + p_2 T_2 \approx p_1 \cdot d^1 \text{ and } p_3 T_3 + p_4 T_4 \approx p_3 \cdot d^2.$$

The mean state duration T_{Mean} can now be expressed by using the QoS demands of Equation (3.1) as

$$T_{Mean} \simeq SFDUR \cdot \begin{pmatrix} p_0 \cdot min\left(\Delta^1_{dem} \cdot \left(1\text{-}\Theta^1_{dem}\right), \Delta^2_{dem} \cdot \left(1\text{-}\Theta^2_{dem}\right)\right) \\ + p_1 \cdot \Theta^1_{dem} \cdot \Delta^1_{dem} + p_3 \cdot \Theta^2_{dem} \cdot \Delta^2_{dem} \end{pmatrix}$$

where p_0, p_1, and p_3 are given through the solution of *P*, see Section B. With this definition of the mean state duration T_{Mean}, the observed throughputs of the players are given by

$$\Theta^{1(2)}_{obs} = SFDUR \cdot \Delta^{1(2)}_{dem} \cdot \Theta^{1(2)}_{dem} \cdot \frac{p_{1(3)}}{T_{Mean}}.$$

Assuming a high offered traffic $\sum_i \Theta^i_{dem} \rightarrow 1$, with $P_{12} \rightarrow 1, P_{34} \rightarrow 1$ the throughput observation of player *i* is calculated as

$$\Theta^i_{obs} = \frac{\Theta^i_{dem} \cdot \Delta^i_{dem}}{\Theta^i_{dem} \cdot \Delta^i_{dem} + \Theta^{-i}_{dem} \cdot \Delta^{-i}_{dem}}. \tag{4.5}$$

The maximum resource allocation period a player may observe due to delayed allocations during an SSG is calculated as

$$\Delta^i_{obs} = \underbrace{\Delta^i_{dem}}_{\text{demanded allocation interval}} + \underbrace{\Delta^{-i}_{dem} \cdot \Theta^{-i}_{dem} + TXOPlimit}_{\text{unwanted increase of allocation interval (delay)}}$$

where the unwanted maximum increase of resource allocation intervals is dependent on the demand of the opponent player as well as the maximum duration of the EDCF-TXOPs. The latter is defined by the TXOPlimit. This TXOPlimit is neglected in the following as it was defined to be relatively small compared to the typical duration of resource allocations of the two players ($TXOPlimit \ll \Delta^i_{dem} \cdot \Theta^i_{dem}$ with $i \in \mathrm{N} = \{1, 2\}$), and further because of the lower priority in medium access through EDCF. Thus, the maximum observed resource allocation period is given by

$$\Delta^{i}_{obs} = \Delta^{i}_{dem} + \Delta^{-i}_{dem} \cdot \Theta^{-i}_{dem}. \tag{4.6}$$

The expected throughput observations $\Theta^{i,-i}_{obs}$ can be approximated by Equation (4.5), and for the observed allocation periods $\Delta^{i,-i}_{obs}$ an upper bound is given by Equation (4.6). In summary, with

$$\Theta^{i}_{obs} \le \Theta^{i}_{dem}, \quad \Delta^{i}_{obs} \ge \Delta^{i}_{dem}, \quad i \in \mathrm{N} = \{1, 2\}$$

the model P results in the following analytical approximation for the observation of an SSG:

$$P := \left(\begin{pmatrix} \Theta^{i}_{dem} \\ \Delta^{i}_{dem} \end{pmatrix}, \begin{pmatrix} \Theta^{-i}_{dem} \\ \Delta^{-i}_{dem} \end{pmatrix} \right) \rightarrow \begin{pmatrix} \Theta^{i}_{obs} = min\left(\Theta^{i}_{dem}, \dfrac{\Theta^{i}_{dem} \cdot \Delta^{i}_{dem}}{\Theta^{i}_{dem} \cdot \Delta^{i}_{dem} + \Theta^{-i}_{dem} \cdot \Delta^{-i}_{dem}} \right) \\ \Delta^{i}_{obs} = \Delta^{i}_{dem} + \Delta^{-i}_{dem} \cdot \Theta^{-i}_{dem} \end{pmatrix}. \tag{4.7}$$

V. Results of the Single Stage Game

In this section, a comparison of the model with simulation results is presented to assess how accurate the Markov model P represents the outcome of the SSG. In simulation, EDCF-background traffic of $1\,Mbit/s$, with a TXOPlimit of $100\mu s$ was assumed. The analytical approximation does not capture the EDCF specifically. With $SFDUR = 200ms$, the maximum duration of the EDCF-TXOPs, defined by the TXOPlimit is smaller than the minimum duration of the resource allocations by the players. Hence, there are only minor influences on the game outcomes that result from the EDCF.

Three different scenarios have been selected to review all relevant configurations. First, results are compared for a scenario where player *1* demands a shorter resource allocation interval $\Delta^{1}_{dem} = 0.02$ than it is demanded by player *2*, $\Delta^{2}_{dem} = 0.03$, that means that $\Delta^{1}_{dem} < \Delta^{2}_{dem}$. Fig. 5 shows the resulting outcomes of an SSG for both players, calculated with the analytical model P, as well as simulated. The demand for share of capacity of player *1* is varied between $\Theta^{1}_{dem} = 0$ and $\Theta^{1}_{dem} = 0.9$. The upper figure of Fig. 5 shows the observed shares of capacity $\Theta^{1,2}_{obs}$ over the varying Θ^{1}_{dem}, and the lower figure shows the observed resource allocation intervals $\Delta^{1,2}_{obs}$ over Θ^{1}_{dem}.

It can be seen that the observed share of capacity increases with increasing demand up to a certain saturation point, according to simulation and analytical approximation (solid lines in the upper figure). The observed share of capacity of player *2* keeps constantly at its demanded level, as long as the channel is not heavily overloaded (dotted lines in the upper figure). With heavy overload ($\Theta^{1}_{dem} > 0.8$), the approximation fails to model the effect of repeated collisions, which in general results in a loss of capacity for the player that demands the longer resource allocations, here the player *2*.

The lower figure in Fig. 5 shows the observed resource allocation intervals $\Delta^{1,2}_{obs}$. It can be seen that the observed resource allocation interval of player *2* increases with the increasing demand for share of capacity of player *1*, which is again indicated by simulation and approximation. Note that an upper limit of the maximum observed resource

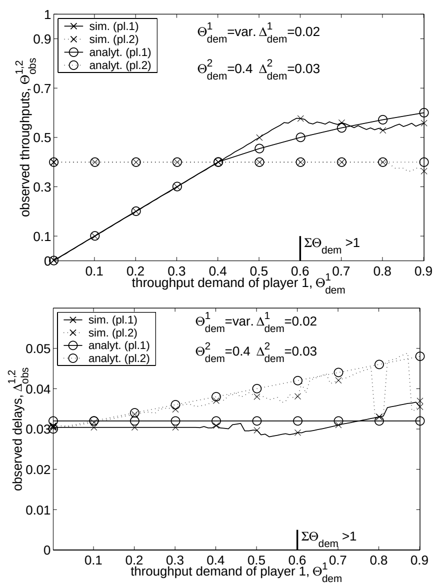

Fig. 5: Resulting observed QoS parameters of an SSG for two interacting players via Θ^{1}_{dem}, calculated with *P,* and simulated. Up: observed share of capacity, down: observed resource allocation interval. In this figure, $\Delta^{1}_{dem} < \Delta^{2}_{dem}$.

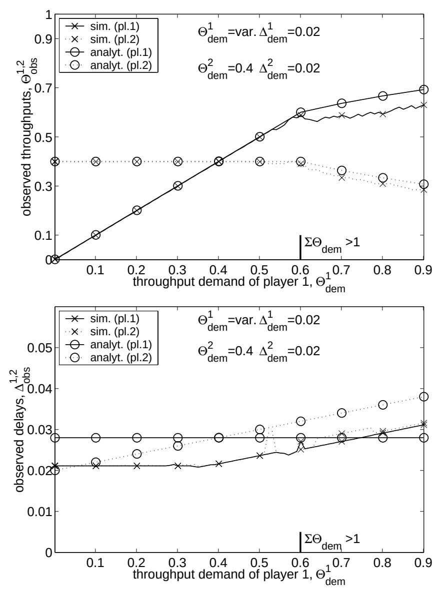

Fig. 6: Resulting observed QoS parameters of an SSG for two interacting players via Θ^{1}_{dem}, calculated with *P,* and simulated. Up: observed share of capacity, down: observed resource allocation interval. In this figure, $\Delta^{1}_{dem} = \Delta^{2}_{dem}$.

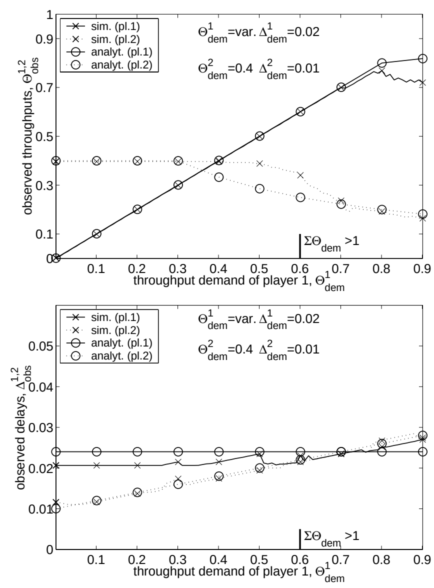

Fig. 7: Resulting observed QoS parameters of an SSG for two interacting players via Θ^{1}_{dem}, calculated with P, and simulated. Up: observed share of capacity, down: observed resource allocation interval. In this figure, $\Delta^{1}_{dem} > \Delta^{2}_{dem}$.

allocation interval is approximated, according to Equation (4.7). The simulation results show some variations of the delay, which are a result of correlated resource allocation times and unpredictable collisions.

Although demanding $\Delta^{1}_{dem} = 0.02$, the player *1* observes a larger resource allocation interval as this is obviously determined by the player that demands the longer resource allocations, here the player *2*. Simulation and analytical approximation show the maximum observed resource allocation interval within one SSG.

Second, in Fig. 6 results are compared for a scenario where player *1* and player *2* demand the same resource allocation interval $\Delta^{1}_{dem} = \Delta^{2}_{dem} = 0.02$. These results of the observed share of capacity show clear similarities in simulation and analytical approximation (upper figure in Fig. 6). But it can be seen that the approximated observations of the maximum resource allocation intervals are rather satisfying for player *1*, but too pessimistic for player *2* (lower figure in Fig. 6). This is due to the limitation that an upper limit rather than an expected value is approximated.

Finally, results are compared for a scenario where player *1* demands a longer resource allocation interval $\Delta^{1}_{dem} = 0.02$ than is demanded by player *2*, $\Delta^{2}_{dem} = 0.01$, that means that $\Delta^{1}_{dem} > \Delta^{2}_{dem}$. From Fig. 7 it can be observed that in this case the simulation results and the analytical approximation are very close to each other in nearly all cases.

VI. CONCLUSION

The Markov model *P* was introduced for an analytical approximation of the outcome (observation) of an SSG. The main motivation was (1) to allow an analysis of the game on a purely analytical basis, and (2) to allow a player to estimate possible outcomes of the game in advance, while decision taking. Both goals are met. The model *P* is accurate enough to capture the statistical characteristics of the SSG. Whereas the model is simple enough to allow players to estimate the outcomes of an upcoming game in advance, this model can also be used for the detailed analysis of the SSG. In addition, the players are able to calculate the outcome of the SSG depending on their own and the opponent's expected action. These results are considered in deciding which action to take and a further interaction of the players is enabled.

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