QoS Support as Utility for Coexisting Wireless LANs

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***Abstract* — The upcoming IEEE 802.11e is an extension of the 802.11 Wireless Local Area Network (WLAN) standard for provisioning of Quality of Service (QoS). This paper discusses the problem of QoS support in 802.11e in coexistence scenarios. As long as a set of 802.11e-stations operate without any other competing stations in the area, QoS can be guaranteed by a central coordinator, using polling techniques. However, in the situation of overlapping sets of 802.11e-stations, all stations support priorities between different data streams, but cannot guarantee any QoS, because of the uncoordinated access to the common radio channel. An approach to model such a competition scenario is the stage-based game model in which players try to maximize their benefits. The extension of the game on multi stage games covers the dynamic effects of the competition. The intention of the model is the definition of an etiquette, i.e., a framework for the player's interaction, to establish cooperation under which adaptive QoS support is achieved.**

ABBREVIATIONS

ACK	*Acknowledgement*
AIFS	*Arbitration Inter Frame Space*
AP	*Access Point*
CA	*Collision Avoidance*
CFP	*Contention Free Period*
CCHC	*Central Controller Hybrid Coordinator*
CF-Poll	*Contention Free – Poll*
CP	*Contention Period*
CSMA	*Carrier Sense Multiple Access*
CW	*Contention Window*
CWmax	*Contention Window Maximum*
CWmin	*Contention Window Minimum*
DCF	*Distributed Coordination Function*
EDCF	*Enhanced DCF*
HC	*Hybrid Coordinator*
HCF	*Hybrid Coordination Function*
IEEE	*Institute of Electrical and Electronics Engineers*
MAC	*Medium Access Control*
MSDU	*MAC Service Data Unit*
NAV	*Network Allocation Vector*
PCF	*Point Coordination Function*
PHY mode	*Physical Layer mode, coding and modulation scheme*
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*
SF	*Superframe*
SFdur	*Superframe Duration*
TBTT	*Target Beacon Transmission Time*
TC	*Traffic Category*
TXOP	*Transmission Opportunity*
WLAN	*Wireless Local Area Network*

I. INTRODUCTION

The IEEE 802.11e is an extension of the 802.11 *Wireless Local Area Network (WLAN)* standard for the *Quality-of-Service (QoS)* provisioning [1],[2],[7],[8]. This new standard provides the means of prioritizing the radio channel access within an infrastructure *Basic Service Set (BSS)* of the IEEE 802.11 WLAN, which is composed of an *Access Point (AP)* and a number of stations associated with the AP. The AP connects its stations with the infrastructure. A BSS that supports the new priority schemes of the 802.11e is referred to as QoS supporting BSS *(QBSS)*. Here, we consider the IEEE 802.11a 5 GHz *physical layer (PHY)*, as explained in [3]. This paper focuses on the coexistence when geographically co-located WLANs share the same radio channel in the so-called overlapping BSS environment. The 802.11 WLANs operate in unlicensed bands and have to share radio resources with other coexisting WLANs, which could be the same kind as we consider in this paper, or a different kind as considered in [2]. The highest priority access to the radio channel is provided by a polling technique as part of 802.11e. This polling technique fails if there are more than one stations trying to poll at the same channel. We address this problem by introducing a framework for policies that aim to establish cooperation between the stations, in order to allow the support of QoS, even if the channel has to be shared between different stations.

The paper is outlined as follows. In the next section the upcoming standard 802.11e is outlined. Simulation results show the throughput degradation in the situation of overlapping stations in Sect. III. Sect. IV discusses the stage model, and Sect. V explains a prediction method that is required for a station to respond to the other station's channel access. The paper ends up with an outlook on multi stage games in Sect. VI and conclusions.

II. THE IEEE 802.11(E) MAC [1]

The basic 802.11 MAC protocol is the *Distributed Coordination Function (DCF)* based on *Carrier Sense Multiple Access (CSMA)*. Stations deliver *MAC Service Data Units (MSDUs)* of arbitrary lengths up to *2304 bytes*, after detecting that there is no other transmission in progress on the channel. However, if two stations detect the channel as free at the same time, a collision occurs. The 802.11 defines a *Collision Avoidance (CA)* mechanism to reduce the probability of such collisions. Before starting a transmission a station has to keep sensing the channel for an additional random time after detecting the channel as being idle for a minimum duration called *DCF Interframe Space (DIFS)*, which is *34 us* for the 802.11a PHY. Only if the channel remains idle for this additional random time period, the station is allowed to initiate its transmission.

For each successful reception of a frame, the receiving station immediately acknowledges the frame reception by sending an *Acknowledgement (ACK)* frame. To reduce the hidden station problem inherent in CSMA networks, the 802.11 also defines a *Request-to-Send/Clear-to-Send (RTS/CTS)* mechanism, which can be used optionally. Between two consecutive frames in the sequence of RTS, CTS, data, and ACK frames, a *Short Interframe Space (SIFS)*, which is *16 us* for 802.11a, gives transceivers the time to turn around. See Fig. 1 for an example of the DCF. It is important to note that SIFS is shorter than DIFS, which gives CTS and ACK frames always the highest priority for the channel access.

There are enhancements to the 802.11 MAC currently under discussion, called the 802.11e, which introduce *Enhanced DCF (EDCF)* and *Hybrid Coordination Function (HCF)* [8]. Stations, which operate under the 802.11e, are called QoS stations, and a QoS station, which works as the centralized controller for all other stations within the same QBSS, is called the *Hybrid Coordinator (HC)*. A QBSS is a BSS, which includes an 802.11e-compliant HC and QoS stations. The HC will typically reside within an 802.11e AP. In the following, we mean an 802.11e-compliant QoS station by a station. The EDCF is a contention-based channel access mechanism of HCF. All the details of the rest of the HCF are beyond the scope of this paper.

With the EDCF, QoS support is realized through the introduction of *Traffic Categories (TCs)*. MSDUs are delivered through multiple backoff instances within one station; each backoff instance is parameterized with TC-specific parameters. Each TC within the stations contends for a *Transmission Opportunity (TXOP)* and independently starts a backoff after detecting the channel being idle for an *Arbitration Interframe Space (AIFS)*, which is dependent on each TC. After waiting for AIFS, each backoff sets a counter to a random number. The minimum size (*CWmin[TC]*) of the CW is another parameter depending on the TC. See Fig. 4 for an illustration of the EDCF parameters.

Another important part of the 802.11e MAC is the TXOP. A TXOP is an interval of time when a station has the right to initiate transmissions, defined by a starting time and a maximum duration. TXOPs are acquired via contention (*EDCF-TXOP*) or granted by the HC via polling (*polled-TXOP*). The duration of an EDCF-TXOP is limited by a QBSS-wide *TXOPlimit* distributed in beacon frames. The polled TXOPs are allocated with highest priority, without any CA, i.e. without any backoff before the poll. The polling scheme requires that there is one HC coordinating the channel, without any other HC in the range of this HC.

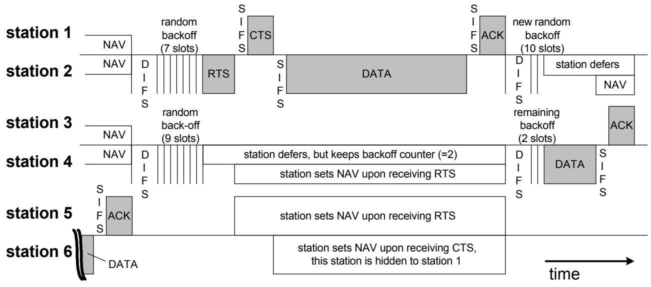

Fig. 1: Timing of the 802.11 DCF. In this example, station 6 cannot detect the RTS frame of the transmitting station 2, but the CTS frame of station 1 [1].

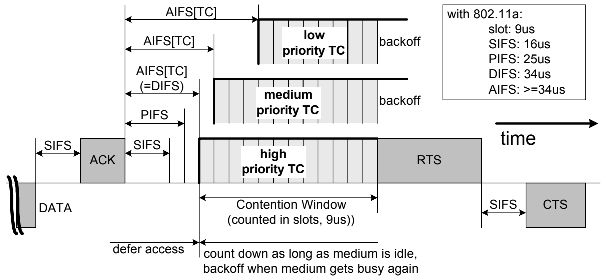

Fig. 2: Multiple parallel backoffs of MSDUs with different priorities. Note that AIFS may be smaller than DIFS. In that case the CW starts at 1 rather than 0, which is the same as AIFS=DIFS [1].

III. Overlapping QBSSs Sharing a Radio Channel and Allocating Resources with Highest Priority

Each TXOP begins either when the channel is determined to be available under the EDCF rules, i.e., after AIFS plus backoff time, or when the station of a QBSS receives a special polling frame, the QoS CF-Poll, from the HC. The QoS CF-Poll from the HC can be sent after a PIFS idle period without any backoff. Therefore, the HC can issue polled TXOPs using its prioritized channel access.

The coexistence problem in 802.11e we are discussing here is illustrated in this section for a simple scenario with two QBSSs sharing the same channel. We use event-driven stochastic simulations to evaluate the performance of 802.11e/a. Fig. 3 shows an OQBSS scenario, and Fig. 4 illustrates the offered traffic, which is the same in both QBSSs. In Fig. 5 the resulting throughput per stream is shown for a period of *150 s* during which the two QBSSs move slowly towards each other, starting with a distance of *d=300 m* until they fully overlap, i.e. *d=0 m*.

The throughputs of the low priority best-effort traffic streams of TC 0 are reduced as soon as the two QBSSs detect each other. This is a desired result, as this allows streams of higher priorities to support their QoS, as can be seen for the differentiated streams (TC 5). The two HCs suffer severely from the fact that there is another HC attempting to allocate TXOPs, i.e. channel resources with highest priority. Fig. 5 shows that the resulting throughputs of the polled streams collapse down to nearly zero, which is a result from unsuccessful resource allocation due to colliding QoS CF-Poll frames.

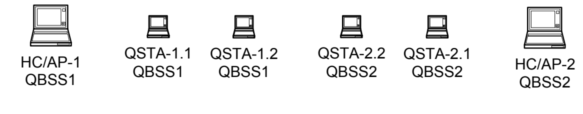

Fig. 3: Scenario of two overlapping QBSSs.

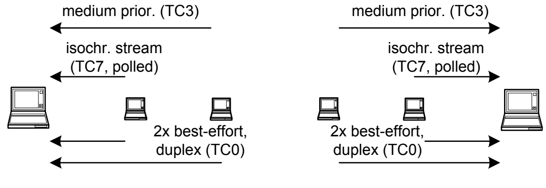

Fig. 4: The offered traffic in the OQBSS scenario is a mix of best-effort and differentiated traffic through EDCF (*1 Mbit/s* per stream) and high priority isochronous streams through polling (*0.128 Mbit/s* per stream).

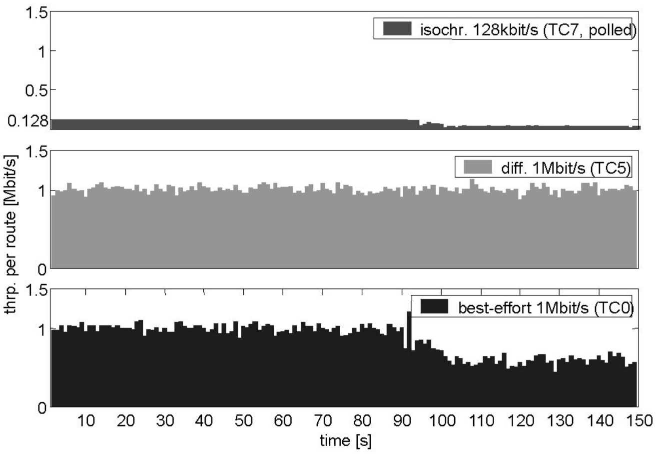

Fig. 5: Resulting throughput per stream. The two QBSSs move towards each other, after around *90 s* the stations mutually interfere with each other.

IV. QOS AS UTILITY

In the following, we discuss a policy framework, which may solve this problem discussed in the previous section. This framework may allow the establishment of coexistence based on mutual support, i.e. cooperation [9],[10].

A. The Coexistence Model

A centrally coordinating station, such as an HC in 802.11e is referred to as *Central Controller Hybrid Coordinator (CCHC)* in the following [2]. We define a dynamic game to study the CCHC coexistence. The game model comprises a set of players, which choose their actions in each period of the game to maximize that period's expected own payoff, given their assessment of their opponent's actions in that particular period [4]. An action of a player is the selection of a certain way of resource allocation by a CCHC. The game model is called dynamic as the players periodically adopt their action demand to the environment after each period of the game. At each game period, a player observes the demand and the action of its opponents together with its own revenue, i.e. payoff. It does not necessarily observe the revenue of other players.

In particular, we take the Cournot competition model approach [4],[5]. A Cournot game in a strategic form consists of a finite set of players, a feasible set of actions for each player, a price function that is common knowledge between the players, and utility functions that give payoffs for each action. Competing CCHCs are modeled as rational players attempting to maximize their payoffs within the Cournot pricing scheme. A payoff is a measurable quantity related to QoS (throughput, delay, delay variation) a player observes after playing the game.

The Cournot competition model relies on the assumption of rational players. Rationality of players means in general that players select the best response to their believe of what action the opponent players select. In other words, a rational player that selects the best response does select that action that maximizes its payoff, given the action of the opponent players. This requires that a rational player knows its opponents' actions before the decision taking of what action to select. This is generally not a realistic assumption, but can be assumed if we take into account that the single stage game is played repeatedly, giving players the chance to estimate the upcoming actions of the opponent players from their past behavior.

Fig. 6 illustrates an 802.11 *superframe (SF)* that we interpret as the single stage game for two players. A CCHC is modeled as a player. Within the 802.11/CCHC protocol stack, the Station Management Entity holds the decision taking player entity. A CCHC's utilization of the radio channel is motivated by the demand of all stations within its QoS supporting BSS, i.e. QBSS. This utilization of the radio channel is attained through selected actions and determines the player's observed payoff. A successfully transmitted beacon begins each single stage of the game; a superframe therefore defines the duration of one single stage. We suppose that the beacon is successfully transmitted by one of the competing CCHCs. The length of the superframe, i.e. the period between two consecutive beacons *(superframe duration, SFdur)*, defines the maximum capacity of the radio channel at respective stages of the game. In repeated single stage games the players try cooperate by performing a Cournot adjustment towards a stable operation point. In such an operation point all CCHCs allocate their TXOPs in a way that in an optimal case allows fair resource sharing. Success of allocation, number and duration of the TXOPs represent the level of cooperation. The demand for resource allocations per CCHC (per player) defines the number, size and starting times of the TXOPs that players try to allocate.

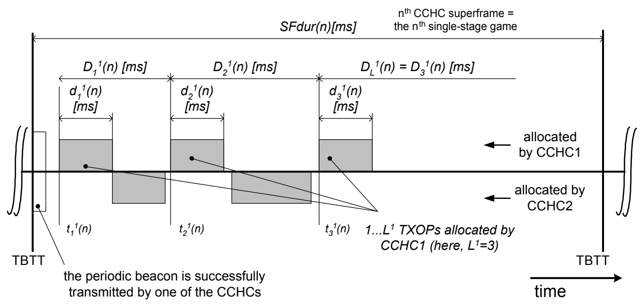

Fig. 6: The n[th] *superframe (SF)* modeled as single stage game with a certain *SF duration (SFdur)*. Typically, multiple single stage games are played repeatedly.

B. Quality of Service as Utility

The QoS parameters we are looking at are throughput, MSDU delivery 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 hypothetically assume that QoS demands change slowly in comparison to the speed of the game, i.e. the decision taking. This assumption allows us to claim stationarity of the underlying decision processes. 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 throughput $\Theta_i(n)$ represents the share of capacity a player i demands at superframe n:

$$\Theta_i(n) = \frac{1}{SFdur(n)} \sum_{l=1}^{L(n)} d_l^i(n), \qquad \text{(IV.1)}$$

where $L(n)$ is the number of allocated TXOPs per superframe n, and $SFdur(n)$ the duration of this superframe in ms. The parameter d_l describes $TXOPdur_l(n)$, the duration of TXOP l, $l=1...L$, in ms. See Fig. 6 for an illustration the parameters. The MSDU delivery delay $\Delta_i(n)$ specifies the maximum delay that the QBSS tolerates at superframe n. In particular, this delay describes the expected maximum delay between two MSDU transmissions due to the interrupted TXOP allocations, neglecting the effect that a transmission itself may fail and require retransmissions:

$$\Delta_i^{\max}(n) = \frac{1}{SFdur(n)} \max\left[D_l^i(n)\right]_{l=1...L(n)-1}, \qquad \text{(IV.2)}$$

where $D_l^i(n) = t_{l+1}^i(n) - t_l^i(n)$ is the time between the starting points of the two TXOPs l and $l+1$ of player i in superframe n, again measured in ms. Note that $D_L^i(n) = t_1^i(n+1) - t_L^i(n)$ exceeds the superframe n.

A utility function for player i is defined over the closed set of actions, A_i that is common for all players and TCs. A typical utility function is shown in Fig. 7. Its shape depends on the QoS requirements (throughput Θ_{req}, delay Δ_{req}) of the player:

$$\begin{aligned} u_i &= u(\Delta)\bullet u(\Theta), \text{ with} \\ u(\Theta) &= \frac{1}{2} + arctan\left[m\bullet\left(\Theta - \Theta_{req}\right)\right]\bullet\frac{1}{\pi} \qquad \text{(IV.3)} \\ u(\Delta) &= 1 - \left(\frac{1}{2} + \bullet arctan\left[m\bullet\left(\Delta - \Delta_{req}\right)\right]\bullet\frac{1}{\pi}\right). \end{aligned}$$

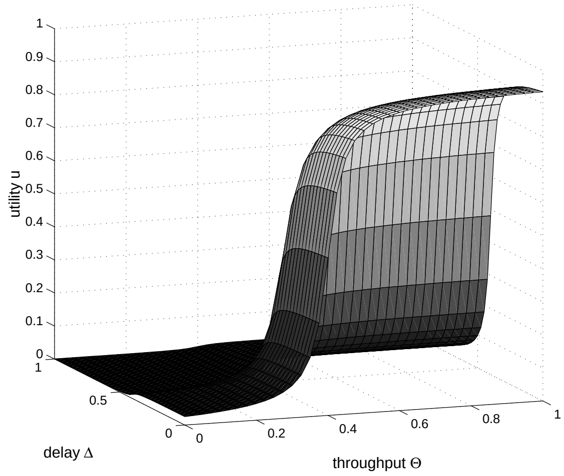

Fig. 7: Utility function. Depending on its demand, a player's utility increases with increasing throughput per superframe and decreasing delay per allocation.

C. Allocation of Resources through QoS CF-Poll

Fig. 8 shows the TXOPs in a SF that results from the resource allocations of two players with different QoS requirements. The SF has a duration of $200\ ms$. Not shown are the TXOPs that are allocated through EDCF. The maximum duration of the EDCF-TXOPs is under control of the players, by using the TXOPlimit. Note that with typical EDCF parameters, the polled TXOPs have always higher priority over the EDCF-TXOPs.

The two players operate with their own utility functions and therefore accept different maximum delays of TXOPs. The demand of a player is calculated at the beginning of a SF based on the history of earlier outcomes, the assessment of the requirements of the opponent's player, and its own QoS requirements. In general, not all demanded TXOP can be successfully allocated by both players due to the competitive access. To illustrate the influence of the QoS parameter on the TXOP allocation of both players and in particular their observed utilities, Fig. 9 shows the observed utilities of the two players. Here, the demanded throughput of player 1 Θ_{req}^1 is increased from 0 to 0.8. At the beginning of a single stage game, both players calculate their demanded TXOPs based on their QoS parameter set and attempt to allocate them. Depending on the opponent's allocation, the TXOP allocations of a player may fail because of collisions or unacceptable delays through the allocation attempts of the opponent player. The allocated TXOPs form the observed QoS parameters set, i.e. the observed utility, which differs from the demanded QoS parameter set depending on the total demand of both players. Player 2 requires $\Theta_{req}^2 = 0.4$, and both players require $\Delta_{req}^{1,2} = 0.05$. It can be seen that for an overloaded channel, the utility of player 1 increases at the cost of utility of player 2.

This undesired situation can be avoided by introducing a price scheme, see Fig. 10 and Fig. 11. Players are charged a price per resource that depends on the overall demand. Fig. 10 illustrated the resulting charges that have to be paid by the players depending on the resources they allocated. The payoff, i.e. *utility - charge*, is the parameter that now has to be considered when allocating resources. With a payoff below 0, a player will not demand too many resources. However, as part of this pricing scheme, a player must estimate the requirements of the opponent player, and must be capable of coordinating the resource allocations in advance. The next two sections discuss means to achieve this characteristic of the player.

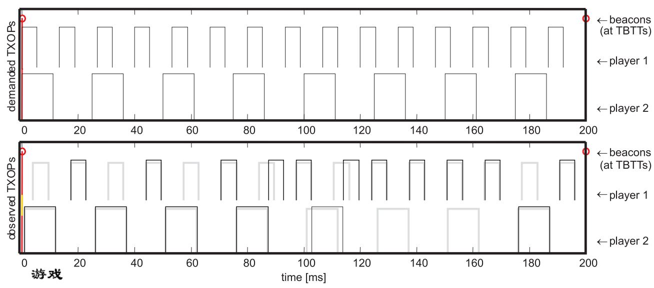

Fig. 8: One SF with demanded (top) and observed (bottom) TXOPs.

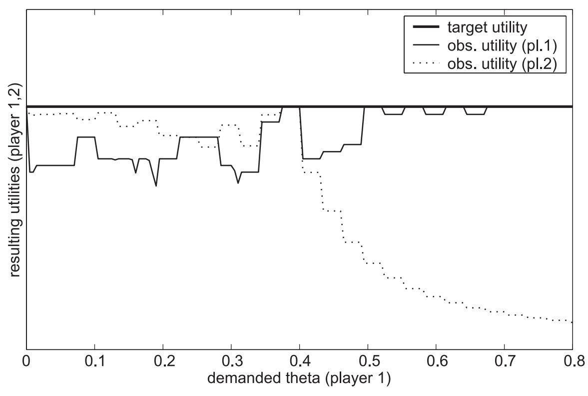

Fig. 9: Observed utilities vs. throughput demand of player 1.

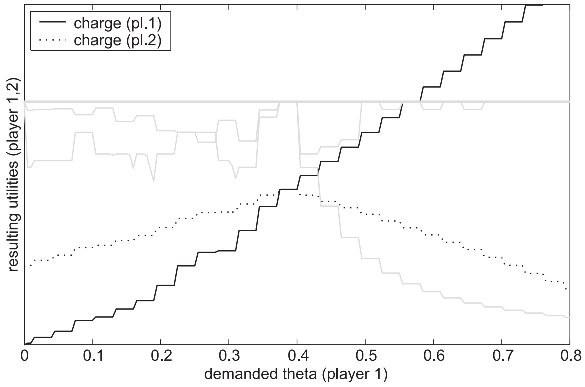

Fig. 10: Resulting price and charges.

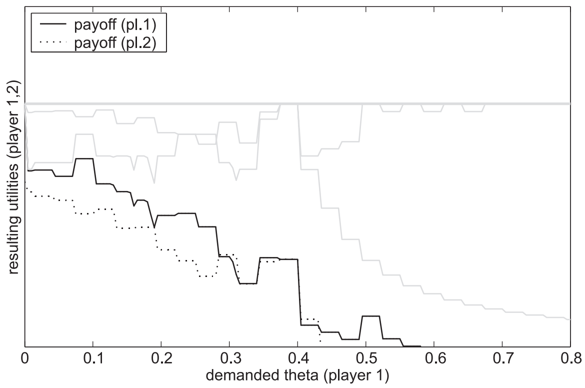

Fig. 11: Resulting payoffs.

V. A METHOD TO PREDICT THE OPPONENT'S FUTURE ALLOCATION OF RESOURCES

It is a requirement for the player's cooperation to avoid that different players attempt to allocate resources at the same time. The resource allocations that have to be coordinated by the coexisting players are initiated with poll frames called *QoS CF-Poll*, which are part of 802.11e. A QoS CF-Poll starts a time interval, called TXOP that is used for MSDU deliveries of time-bounded services, i.e., services that require QoS support. Poll frames are transmitted immediately after detecting the channel as being idle for PIFS, without any collision avoidance mechanism, i.e., random backoff before the poll. In case of more than one player requiring resources at the same time, their poll frames will collide. To reduce the collision probability of poll frames, a technique to predict future allocations from the history of past resource allocations is applied in each player entity. This technique is explained in this section.

A. Prediction method

The algorithm uses the time correlation of the poll frames that have been already transmitted by the opponent player. At each time when a player detects the resource allocation of any other player, it updates its assessment of when to expect the next allocation from this particular player. The available information that is used for the prediction are (1) the set of times when the past poll frames within the ongoing superframe have been transmitted, and (2) the time of the last *TBTT*, i.e. the last beacon transmission. Thus, only information that is part of the single stage game is used.

Upon detecting a poll frame, the history of the ongoing single stage game is transformed into a discrete sequence of elements $s(n)$, where $s(n)=1$ if a poll frame was detected in the time interval $[n*aTimeUnit;\ (n+1)*aTimeUnit]$, and $s(n)=0$ otherwise:

$$s(n) \in [0;1], \quad n = 0 \ldots N, \qquad N = \frac{now - lastTBTT}{aTimeUnit}. \tag{IV.4}$$

The value of *aTimeUnit* determines the precision of the sequence and is set to a value below the *TXOPlimit*, typically $100\ \mu s$. The TXOPlimit defines the maximum duration of resource allocations based on EDCF, see Sect. II. In equation (IV.4), *now* and *lastTBTT* are the boundaries defining the interval that is represented by $s(n)$. With an appropriate window size W, the autocorrelation properties of $s(n)$ is used to calculate the estimated time of the next poll frame, i.e., the estimated time of the next attempt to allocate resources. With

$$\varphi(l) = \frac{1}{2W+1} \sum_{m=N-W}^{W} s(m) \cdot s(m+l),$$

any local maximum of the right-hand side of $\varphi(l)$, $max\left[\varphi(l=L)\big|_{l>0}\right] \Rightarrow L$ indicates a periodic detection of polls. Assuming that the demand of an opponent player does not change during a single stage game, the periodic time distances of past allocation attempts are used to predict the possible next attempt of resource allocation:

$$aNextPollTime = now + aTimeUnit \cdot s(l = L),$$

where *aNextPollTime* is the point of time when the opponent player is expected to initiate its next resource allocation.

B. Example

Fig. 12 illustrates one superframe with duration of *200 ms*, where two players are periodically allocating resources, i.e., TXOPs. The thick lines in the lower part of the figure represent the times when player 1 expects poll frames from player 2. It can be seen that the fourth prediction performed at *now=88 ms* and predicting a poll at *100 ms* fails as the respective TXOP of player 2 is delayed. In general, any such deviation from the expected period has negative implications on the accuracy of later predictions. This is not the case in the simplified example in the figure. Further, it can be seen in Fig. 12 that player 1 starts its predictions only after detecting a minimum of two polls from player 2. To illustrate the usage of the sequence $s(n)$, the correlation function used at *now=88 ms* is shown in Fig. 13 as an example. The same superframe as before is shown. The first side-lobe with a significant magnitude is used to estimate the next poll from player 2.

C. Limitations

The prediction technique helps to reduce the probability that poll frames collide. However, any prediction fails at the beginning of a superframe and improves its accuracy with time, as long as an opponent player allocates resources periodically. Another limiting factor is the observed periodicity of poll frames that are transmitted by a specific player. The periods of allocation attempts, and any deviation from it, necessarily depend on the activity of other players, and the TXOPlimit. As long as only two players attempt to allocate resources, those deviations result from TXOPs that are allocated by the predicting player itself, which can be taken into account for more accurate prediction.

There are other ways to improve the accuracy of the prediction. As explained before, so far it uses only the set of times when the opponent player attempted to allocate resources in the past, during the on-going superframe. More information that may help to improve the accuracy of the predictions is the MAC-Ids of polled stations, the durations of the allocated TXOPs, and the history of past superframes.

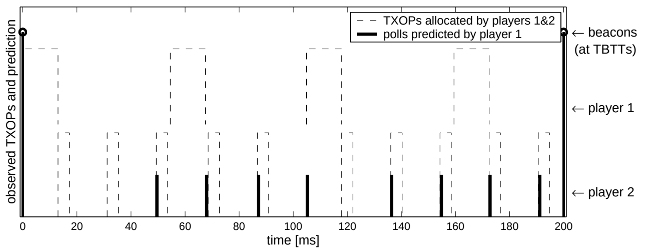

Fig. 12: Allocated TXOPs of player 1 (top) and player 2 (bottom) and predicted polls from player 2.

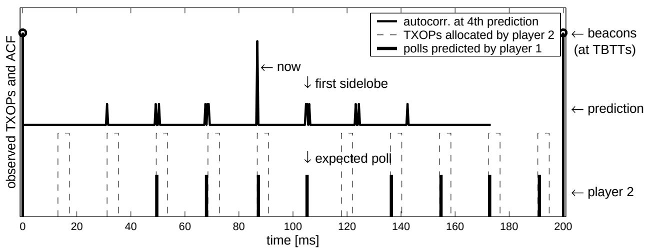

Fig. 13: Autocorrelation used for estimating the next poll at *now=88 ms (4th prediction)*. Window size *W=88*, *aTimeUnit=500us*.

VI. Establishing Cooperation

Repeatedly played single stage games allow the analysis of the dynamic effects of competition. The stage game model is characterized through asymmetric information: the players are aware of their own demand and have no information about the demand of their opponents. In observing the opponent's TXOP allocations, they are able to estimate the demanded QoS parameters of the other players. With increasing duration of a game the estimation, based on the growing amount of observed opponent TXOP allocations, gets more accurate, as long as the QoS requirements do not change significantly during a the game iterations. The knowledge of the opponent's demand enables the player to interact: It depends on the player's strategy if they interfere each other or if they cooperate. Knowing the opponent's time of trying to allocate a TXOP (by means of the predictor as explained in the previous section), the player is able on the one hand to prevent this in allocating a TXOP earlier, or to delay the opponent's allocation attempt to a specific length of time. On the other hand, an instantaneous withdraw of allocations is possible to let the opponent access the channel. This graceful degradation of the own demand can be seen as an offer of cooperation. Cooperation can be successfully established if all players can profit from it, i.e. have a higher payoff in cooperation, than without it. Free raiders, i.e. players who leave this game wide cooperation, may be punished in being purposely delayed when they attempt to allocate their TXOPs (again using the prediction method described in the previous section).

Significantly important for a successful establishment of cooperation is a simple acting of the players. The simpler the own strategy, influencing the own actions, the easier is it for the other players to realize this strategy. This is mandatory for a stable point, because cooperation can only be established if the other players are able to react. The action of one player has to be predictable, so that the other players are able to find a best response to this action. A simple, easy to recognize strategy is for example TIT-FOR-TAT described in [6]. A complex strategy handicaps the observation and realization of itself. A complicated strategy is in this way an obstacle for cooperation. A cooperating player tries to reveal its strategy to enable the other players to predict its actions.

VII. Conclusions

A framework for the analysis of coexistence of WLANs based on 802.11e is introduced. As approach to model a competition scenario between overlapping sets of 802.11e-stations a stage-based game model is selected. A first analysis of the model indicates that, together with some means of the player instances, policies can be established to support QoS, even if the channel is shared by competing WLANs. Future work will focus on an equilibrium analysis of the single stage game, and multi stage games to investigate social phenomena of interaction.

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