Multiple access protocol misbehavior in WLANs

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***Abstract*— Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is probably the most widespread multiple access protocol in use today, mainly due to the tremendous success of the IEEE 802.11 suite of standards. Until now most of the studies done about the protocol have focused on maximizing the performance. However as the bands become more crowded and the user terminals become easier to reconfigure, it is reasonable to assume that users will try to modify their equipment in order to achieve better performance, even if this may be in expense of the other users. The focus of this paper is from an overall network point of view, where two competing networks are considered. The competing network scenarios are modeled by the use of game theory, applying simple and repeated form games. The outcome of the games is described by the Nash Equilibrium (NE). We argue that by modifying the contention window, based on respective network parameters and by simple interaction between the contending networks, a superior performance than provided by the standard can be obtained. In the first part of the paper we compare the performance of a network following the standard to a network that is maximizing its throughput. The result is that by modifying the contention window size it is actually possible to achieve better performance than for a network that adheres to the standard. We then continue on analyzing the case where both networks try to achieve maximum performance in a selfish manner.**

***Index Terms*— 802.11, WLAN, access misbehavior, game theory**

I. Introduction

Wireless LAN operators are interested in obtaining sufficient resource access to provide their user's demands. Nowadays, different mechanisms are standardized to provide equitable resource sharing among the users in unlicensed wireless networks. The focus of the paper is on a geographical area with two coexistent operators, who access the channel according to the IEEE 802.11a standard. This possible scenario occurs frequently in the field of public access networks like airport terminals, train stations, etc. An operator is defined as a single cell consisting of an Access Point (AP) and its allocated STAtions (STA). Such a network deployment is defined as an Infrastructure Basic Service Set (IsBSS). Assuming that the competing IsBSS access the channel according to the standardized CSMA/CA protocol, the medium is equitable shared. The systemwide goal of a misbehaving operator is to achieve higher throughput for the users. The enhanced performance is achieved by modifying the existing access protocol, i.e by adapting the Contention Window (CW) size to the traffic conditions. Both of the operators are therefore considered to operate in saturated conditions, e.q each node within the network has always a packet to transmit. Throughout the paper, we define a node as either an AP or a STA. Focusing on the CSMA protocol of the IEEE 802.11a standard, the contending nodes imply a random backoff period to resolve contention in order to prevent packet collisions. The goal of an operator is now to constantly modify its backoff period to achieve higher channel access probability with reference to the opponent network. Considering the fact that both operators are able to modify the access probability of their assigned nodes, the scenario becomes more complex. To model such a competitive case deployment, we make use of Game Theory (GT) in form of Single Stage Games (SSG) as well as Multiple Stage Games (MSG).

The following section describes the existing IEEE 802.11a CSMA protocol and the relevant parameters. Assumptions, simulation models as well as analytical models are described in the proximate section. The achieved results with reference to the game theoretical models are described in the latter sections of the paper.

II. The MAC layer of IEEE 802.11a standard

The IEEE802.11a defines the basic MAC protocol, which guarantees equitably shared medium allocation among the contending stations by using the CSMA/CA access mechanism. If a contending node detects the medium to be busy it defers and gets back into contention the next time the medium is idle. If the medium is idle longer than the Distributed Interframe Space (DIFS) [1], the station is backing off and starts its transmission when the backoff-counter reaches zero. Due to the random allocation of a backoff to each contending node, the possibility of a collision is small. The node having the smallest backoff allocated wins the contention, while the other need to wait for the next contention round, taking place after the packet transmission. The MAC protocol further implements a positive ACKnowledgment (ACK) transmission upon successful transmission of a data packet. Fig. 1 depicts the sequence of a successful data packet transmission. The size

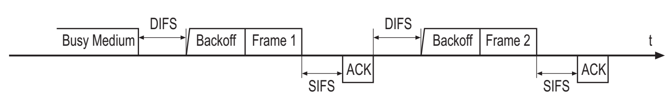

Fig. 1. Successful frame transmission

of the backoff itself is a random integer drawn from a uniform distribution over the interval [0,CW]. CW is the Contention Window size and has a standardized initial value of CW_{min}. For an unsuccessful transmission, a retransmission is initiated and a new backoff window assigned. The backoff window is randomly selected, based on the updated CW size. The CW size itself is dependent on the retransmission attempt (TR_n):

$$\text{CW}_{TR_{n+1}} = 2 \cdot \text{CW}_{TR_n} + 1 \qquad (1)$$

CW is increased every retransmission attempt until it reaches CW_{max} and stays on this value for every further unsuccessful retransmission. After a successful transmission the value is reset to CW_{min}. Moreover, the standard defines a retransmission limit [1]. The packet is dropped when the limit is exceeded.

III. Game Theory

Game Theory provides a powerful mathematical tool to provide conflict resolutions in competitive scenarios. The models are distinguished by the mapping of the actual interaction process to the players. Considering the basic model, a game contains the following components:

- Two or more players, i.e. the contending operators
- Each player has an action set to chose a specific action from, i.e. the different CW sizes
- Each player's action dependent outcome is defined by the utility function, i.e. the resulting saturation throughput

A single interaction between players is modeled by a Single Stage Game (SSG). Considering a repeated interaction over a finite or infinite time space, Multi Stage Game (MSG) models are applied. An important aspect of multi stage games is, that a user can decide upon its behavior in each state and base its decision upon current measurements, the history of the game as well as the achieved results. By investigating infinite repeated games, we introduce a discounting factor in order to model the uncertainty of the future. Since the players act purely rational, we can assume that present payoffs are worth more than future payoffs. We define the discounting factor $\delta \in [0, 1]$, showing how much a payoff of 1 unit in the current stage is worth in the next stage. The total achievable throughput can be computed:

$$S_{i,0} + \delta S_{i,1} + \delta^2 S_{i,2} + \ldots + \delta^\infty S_{i,\infty} = \sum_{t=0}^{\infty} \delta^t S_{i,t} \quad (2)$$

where δ^t is the discounting factor and $S_{i,t}$ is the saturation throughput of user i at stage t. The value of the factor basically depends on the traffic characteristics. Since we assume equal distributed traffic with identical arrival process, the discounting factor is defined to be constant throughout the game.

A. Prisoner's dilemma

In order to describe the results of the investigations, we introduce the Prisoner's Dilemma (PD) based on a basic example [2]. The PD model describes a reciprocal conflict scenario of two criminals, arrested for a crime. The criminals are kept in different cells: hence, they are not able to communicate throughout the process. If both suspects cooperate (C), they back each other and therefore receive moderate sentences. If one implicates the other, i.e. he defects (D), he receives an acquittal, while the latter is sentenced for life. A general implication of the players, results in severe punishment for both. Table I reflects the numerical interpretation of the described scenario, where player one is represented by the rows and player two by the columns. Moreover, each cell in the matrix contains two values: the left one is the row player's sentence, the right one the column player's sentence. With reference to table II, we denote the individual payoff if both players cooperate as 'R' (Reward). If both players

	cooperate	defect
cooperate	(5,5)	(25,0)
defect	(0,25)	(15,15)

TABLE I
Prisoner's dilemma

defect, they both earn the payoff 'P' (Punishment). If one player cooperates and the other defects, former obtains payoff 'M' (Mystified) and latter payoff 'T' (Temptation). Moreover,

	cooperate	defect
cooperate	R,R	M,T
defect	T,M	P,P

TABLE II
Payoff relations within prisoner's dilemma

the PD is characterized by the following conditions:

$$T > R > P > M \quad (3)$$

$$2R > T + M \quad (4)$$

where the second condition shows that in a repeated process, both player gain higher payoff if they cooperate than if they mutually defect and then share the total payoff. If there is no communication between the players, they both choose strategy D in order to maximize the achievable minimum payoff. This results in a payoff less than obtainable by a common choice for cooperation and therefore is known as the prisoner's dilemma. Due to repetitive interaction between the players, known as the alternating continuous PD, we try to achieve a basic way of communication in order to achieve cooperation.

IV. System model

As previously mentioned, the investigations are focused on a coexistence of two competing operators. An operator is modeled by an AP and and a variable number of associated nodes. To investigate the consequences of access misbehavior we derived an analytical model. In order to justify the analytical model, we further implemented a simulation model, where all the MAC parameters are taken from [1].

A. Analytical model

The investigations of the analytical model are based on Bianchi's [3] saturation model of the 802.11a protocol. In this model, Bianchi focused on a scenario where all the involved nodes exhibit identical access behavior. Since in this paper the focus lies on competitive access between two or more networks, the existing model needs to be extended. To estimate the throughput of IEEE 802.11a with no misbehaving nodes, Bianchi applied a two-dimensional Markov Chain of m backoff stages, where each stage represents the time of the backoff counter of each node. A transition between the states takes place upon a successful, respectively collided transmission [3]. The access probability τ of a node can be derived upon the stationary distribution of the chain,

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \quad (5)$$

where p is the conditional collision probability, W is the initial contention window size CW_{min} and m is the maximum back-off stage. For the applications referring to the standard within this paper, we set m equal to 6. If we consider misbehaving nodes using a fixed CW, regardless of their retransmission state $(m = 0)$, 5 can be simplified to the following expression.

$$\tau = \frac{2}{W+1} \tag{6}$$

The throughput calculations are based on the normalized throughput S, which is defined as the fraction of time where the channel is successfully used to transmit data. Based on the access probability of each node, we can compute the probability that there is at least one transmission in a specific time slot. Focusing on a scenario with M competitive operators, possessing n_k nodes applying different contention windows cw_k this probability is given by:

$$P_{tr} = 1 - \prod_{k=1}^{M} (1-\tau_k)^{n_k} \tag{7}$$

The probability P_{si}, that a transmission initiated by network i is successful is given by the probability that exactly one node of network i is transmitting, whereas the nodes of the competing networks (n_k) remain inactive.

$$P_{si} = n_i \tau_i (1-\tau_i)^{(n_i-1)} \prod_{k=1, k\neq i}^{M} (1-\tau_k)^{n_k} \tag{8}$$

Let us now define the probability of a successful data transmission P_s regarding all the competing networks. To obtain P_s, we need to compute the probability of the union of the individual probabilities of successful data transmission (P_{si}) [4, p.34]. Let us therefore define A_i as the event of a successful individual transmission of network i ($P_{si} = P\left[A_i\right]$).

$$P\left[\bigcup_{i=1}^{M} A_i\right] = \sum_{j=1}^{M} P\left[A_j\right] - \sum_{j<i} P\left[A_j \cap A_i\right] + \dots \tag{9}$$

$$+(-1)^{M+1} P\left[A_1 \cap \dots \cap A_M\right] \tag{10}$$

Regarding the fact, that the probability of more than one network successfully transmitting in the same time slot is equal to zero, the expression is simplified to:

$$P\left[\bigcup_{i=1}^{M} A_i\right] = \sum_{i=1}^{M} P\left[A_i\right] \tag{11}$$

$$P_s = \sum_{i=1}^{M} P_{si} \tag{12}$$

Focusing on two competing operators possessing n_1 respectively n_2 number of nodes, applying CW_1, CW_2 the expressions 7, 8 and 12 can be rewritten as:

$$P_{tr} = 1-(1-\tau_1)^{n_1}(1-\tau_2)^{n_2} \tag{13}$$

$$P_{s1} = n_1\tau_1(1-\tau_1)^{(n_1-1)}(1-\tau_2)^{n_2} \tag{14}$$

$$P_{s2} = n_2\tau_2(1-\tau_2)^{(n_2-1)}(1-\tau_1)^{n_1} \tag{15}$$

$$P_s = P_{s1} + P_{s2} \tag{16}$$

The normalized throughput S can now be express as the ratio

$$S = \frac{E[\text{payload information transmitted in a slot time}]}{E[\text{length of a slot time}]} \tag{17}$$

The average amount of payload information within network i transmitted in a slot time is $P_{si}L$, since a successful transmission occurs in a slot time with probability P_{si}. Further on a fixed packet size of L is assumed within each transmission attempt. The average length of a slot time is based on the fact that with probability $1-P_{tr}$ the slot is empty, with probability P_s it contains a successful transmission, and with probability $1-P_s$ a collision can occur. The throughput for network i can be written as

$$S_i = \frac{P_{si}L}{(1-P_{tr})\sigma + P_sT_s + (1-P_s)T_c} \tag{18}$$

where, T_s is time time needed for a successful transmission, T_c the time a channel is busy due to a collision, and σ is the duration of an empty time slot. As previously mentioned, L represents the data packet size which is assumed to be fixed 256 bytes for each transmission.

B. Simulation model

This section describes the models, deduced from the IEEE 802.11a standard, we implemented in the simulator.

1) Traffic model: Both of the operators are assumed to operate in saturated conditions. Hence, each node always has a packet to transmit upon successful transmition. The investigations are therefore solely focused on the achievable saturation throughput from the systems point of view. No delay constraints are considered.

2) User distribution: The distribution of the nodes is considered to be uniform over the area. The user allocation is deemed to be static and unchanged throughout the investigations. Further on the size of the area was chosen that no hidden terminals occur. Hence, a collision can only appear due to identical backoff-values of the contending nodes.

3) PHY layer: We assume perfect channel conditions and fixed modulation level for all the transmissions. Therefore the length of a successful packet transmition remains constant for all the contending nodes. Each transmitted packet is chosen to be 256 byte. The relevant parameters for implementing the transmission sequences (Fig. 1) are taken from [1].

V. Performance Results

The results are focused on two different approaches of the misbehaving operators. In the first approach, we analyze the superior performance an operator can gain due to the adaptive channel access in expense of its rival. The second approach investigates the scenario, where both of the operators have the ability to misbehave, i.e they both can adapt the CW size.

A. Standard access vs adaptive access

Fig. 2 shows the individual saturation throughput S of both networks versus the CW size of the misbehaving network. We therefore denote the network operating according to the standard as N1 and the misbehaving network as N2. Two different network sizes are considered (7 STAs + 1AP and 10 STAs + 1AP for each network). Focusing on the characteristics of S(N2), it is straight forward that the operating point N2 is seeking for is given by the maximum of the concave curves. Moreover, the graphs clearly show that this operating point depends on the overall number of contending nodes of both networks. The numerical values of the two operating points show, that N2 gains superior performance due to the adaptive modification of the CW size. Fig. 2 further indicates that the results from the analytical model fit very accurately with the empirical results deduced from the simulation model.

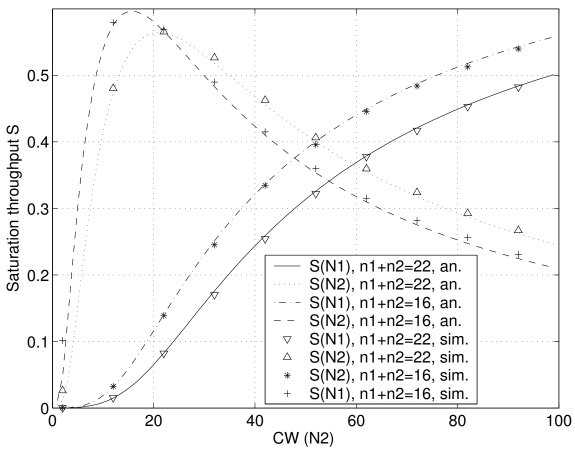

Fig. 2. Throughput of N1 and N2

B. Adaptive access vs. adaptive access

Fig. 3 depicts the saturation throughput dependent on the CW size. The solid line equals to the sum of the individual throughputs ($S(N1)+S(N2)$), considering that both networks apply an identical but variable CW size. The line achieves a maximum of 0.79 at a CW size of 90 (CW(N1)=CW(N2)=90). This point is defined as the maximum achievable S, where the resource is equitably shared. The saturation throughput of the individual network is represented by the dotted line. Networks act cooperatively seek to operate in this maximum which results in a superior performance, compared to the standardized CSMA/CA DCF operation. Specifically for scenarios with higher density of contenting STAs (> 20) the effect becomes more significant.

A further interesting point is to investigate possible gain due to unilateral deviation from the operating point by one of the networks. The dashed line plots S(N1) as a function of CW(N1), whereas N2 is working at the operating point and therefore is obliged to set its CW to CW(N2)=90. S(N1) shows that by choosing CW(N1)$<$CW(N2), the saturation throughput of N1 is unilaterally increasing. A maximum of 0.567 is reached, for a CW(N1) of 24. A further decrease of the CW size results in a decrease of S(N1) due to the increasing collision probability. Focusing on the range where CW(N1)$>$CW(N2) we can ascertain an increase of S(N2) in expense of S(N1). This behavior stems from the fact that we decrease the access probability of N1 by increasing CW(N1).

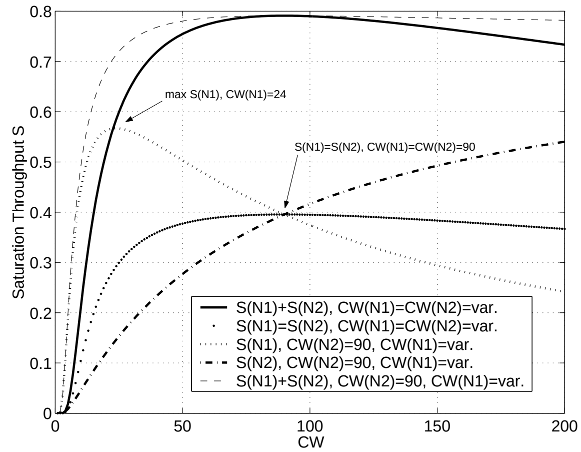

Fig. 3. Saturation throughput analysis

VI. Game Theoretical Approach

A. Single stage game analysis

Considering a scenario with no feedback, i.e. the networks can only modify their contention window once, both networks act in a selfish manner and choose the contention window size maximizing their throughput. This type of interaction can be formulated as a single stage game. Due to the competitive medium access this strategy results in a throughput lower than provided by the standard. This type of network behavior stems from the uncertainty upon the rivals action and can be formulated as the prisoner's dilemma [2]. With reference to the previous section, the scenario of two networks, adaptively modifying the CW size, is modeled in a single stage game. Table III shows the resulting throughput for all possible combinations of actions. If both networks cooperate and access the channel applying the same CW, they gain an individual relative throughput of $0,396$. In the case where both networks implement the 802.11a protocol, a relative saturation throughput of $0,365$ could only be provided. If one of the networks acts selfishly, it obtains a throughput of $0,567$ whereas the throughput of the cooperative network decreases to $0,147$. If both network act selfishly, the individual throughput equals $0,293$. The unique Nash Equilibrium indicates, that both operators should act selfishly (S,S). However, there exists a better solution where both network cooperate (C,C). To end up in this solution, a minimum of cooperation or trust is necessary, which is not conceivable in a single stage game, though. Further on, such a solution is not very stable due to the fact that a player can gain major benefit if he misbehaves. The solution concept of the game is given as the minimax strategy [5, p.83]. Applying the minimax concept, a player chooses the strategy that maximizes it's minimal payoff. Therefore the stable point

N1 ↓ N2 →	C	S
C	(0,396/0,396)	(0,147/0,567)
S	(0,567/0,147)	(0,293/0,293)

TABLE III
Game scenario

of the game is where both players act selfish. The model shows us that the achievable throughput decreases, if both network apply misbehavioral access strategies, given that there is no cooperation or primitive way of mutual communication. To model mutual communication, the prisoner's dilemma is reformulated in a repeated single stage game, known as a multi stage game.

B. Multi stage game analysis

Since none of the networks is interested in the operating point described in the previous section, they both have an incentive to cooperate in order to achieve higher throughput. To achieve cooperation, some simple interaction between the players is necessary. In the last part of the paper we address this problem by modeling the networks competitive scenario as a sequence of single stage games, known as infinite multi stage games [5]. Now one network has the possibility of punishing the other network if that network misbehaves. The investigations show that cooperation is in fact the better strategy for most cases if we consider infinite multi stage games.

The single stage game analysis has shown that we end up in a prisoner's dilemma, where a selfish action for both players appears to be the NE strategy. With the repeated prisoner's dilemma we try to achieve some cooperation in order to obtain a higher saturation throughput. Therefore we make use of the TFT [2] and the GRIM [6] trigger strategies. In the following sections, we investigate the GRIM and TFT strategies in order to evaluate whether they are a NE.

1) TFT Strategy: The TFT strategy, is a NE strategy, if none of the players can profitably, unilaterally deviate by choosing another strategy. Since the TFT strategy is based on cooperation, it is interesting to investigate whether a player can profit while acting selfishly throughout the whole game (ALLS). The result for a constant selfish action is:

$$S_i(\text{ALLS}\,|\text{TFT}) > S_i(\text{TFT}\,|\text{TFT}) \tag{19}$$
$$S_{SC} + \frac{\delta}{1-\delta}S_{SS} > \frac{1}{1-\delta}S_{CC} \tag{20}$$
$$0.624 > \delta \tag{21}$$

The notations as well as the numerical values are taken from table III. The result shows that a player will continuously act selfish beginning from the first stage if his discounting factor is smaller than 0.624. Another possible scenario is to act selfish in a single stage L of the game (SEFL).

$$S_i(\text{SEFL}\,|\text{TFT}) > S_i(\text{TFT}\,|\text{TFT}) \tag{22}$$
$$S_{SC}\delta^L + S_{CS}\delta^{L+1} > S_{CC}\delta^L + S_{CC}\delta^{L+1} \tag{23}$$
$$0.687 > \delta \tag{24}$$

Focusing on the two results, we can show that for a discounting factor $\delta > 0.687$ we can sustain TFT against a single selfish action (SEFL) as well as continuous selfish actions (ALLS). Therefore, TFT is a NE if the discounting factor is $\delta > 0.687$.

2) GRIM Strategy: To investigate the GRIM strategy, we make use of the same selfish action types like in the previous section. In the case of constant selfish action $S_i(\text{ALLS}\,|\text{TFT}) > S_i(\text{TFT}\,|\text{TFT})$, we obtain identical results to the TFT case ($0.624 > \delta$). The second strategy of selfish actions is defined by a continues selfish action, triggered at stage L (SEFL). The payoffs therefore only differ from stage L on:

$$S_i(\text{SEFL}\,|\text{GRIM}) > S_i(\text{GRIM}\,|\text{GRIM}) \tag{25}$$
$$S_{SC}\delta^L + S_{SS}\frac{\delta^{L+1}}{1-\delta} > S_{CC}\frac{\delta^L}{1-\delta} \tag{26}$$
$$0.624 > \delta \tag{27}$$

The results show, that for a discounting factor $\delta > 0.624$ the GRIM strategy can sustain against single and continuous selfish actions (ALLS). The GRIM strategy is a NE if $\delta > 0.624$.

We can deduce that for the specific scenario, the GRIM strategy is more ”robust” against attempts of selfish actions. The more tempting it is to act selfish, the higher a player needs to value the future in order to sustain cooperation.

VII. Conclusions

The results have shown that the achievable saturation throughput of the standardized IEEE 802.11a protocol depends on the number of contending stations. Due to the adaptive modification of the CW, a network can permanently provide a maximal achievable saturation throughput of ≈ 0.8, independent of the network size.

Considering the scenario of two networks, where N1 accesses the channel according to the standardized DCF and N2 adapts the CW in order to achieve maximal saturation, N2 considerably outperforms N1.

If both networks have the ability to adapt their CW to the traffic conditions, the scenarios becomes different. The resulting interaction can be modeled by a prisoner's dilemma, resulting in lower performance than provided by the standard. This performance loss is a result of lacking information between the contending networks. Due to the repeated interaction, modeled by a repeated prisoner's dilemma, the networks create a basic way of communication which results in increased performance. Under some specific assumptions and trigger strategies, the overall throughput outperforms the standard.

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