A Game Theoretic evaluation of Rate Adaptation strategies for IEEE 802.11 based Wireless LANs

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ABSTRACT

Rate Adaptation (RA) for 802.11 has been deeply investigated in the past, in particular with the aim of achieving optimal RA with respect not only to channel-related errors but also to contention-related issues (i.e., collisions and variations in medium access times). Most of prior work in this field considered only RA from the point of view of a single node, i.e., evaluating the performance of different RA strategies adopted by the considered node in scenarios where other nodes use a fixed rate setting. In this paper, we analyze from a Game Theoretic perspective the case in which all users simultaneously perform RA. We show that state of the art strategies such as Goodput Optimal Rate Adaptation (GORA), in which every user selfishly tries to maximize his own performance accounting for issues such as collisions and medium access times, actually often results in degraded performance for all users, whereas simpler SNR-based RA schemes, which have been long regarded as sub-optimal, are actually much more robust.

Categories and Subject Descriptors

C.2.1 [**Computer-Communications Networks**]:
Network Architecture and Design – *Wireless Networks*

General Terms

Algorithms, Design, Theory

Keywords

Rate Adaptation, Game Theory, Wireless LAN

1. INTRODUCTION

In recent years, there has been a significant amount of research on Rate Adaptation (RA) algorithms. Most initial work in this area focused on the case of a single sender-receiver pair, which has been deeply investigated [1–6]. In this particular scenario, frame losses on the radio link are due to noise only; therefore, it is effective to choose the rate based only on the value of the Signal-to-Noise Ratio (SNR) seen by the receiver.[1] In presence of multiple users that compete for the medium, however, the performance experienced by each user is not only determined by the radio propagation conditions but also depends on MAC collisions and variable medium access time. Recently, it has often been argued that, due to these issues, SNR-based RA strategies are sub-optimal in congested WLAN scenarios. As a consequence, several new RA schemes have been proposed to solve this problem and have been claimed to achieve superior performance with respect to SNR-based schemes in scenarios where collisions and medium access times are a major issue [7–9]. A common trait among these schemes is that every mobile node in the network performs RA with the aim of enhancing its own performance. When dealing with contention-based medium access solutions, such as the CSMA-CA protocol on which IEEE 802.11 is based, one might wonder whether the RA performed by each user separately does indeed result in a joint RA strategy which is optimal for the wireless network as a whole. We note that this issue has not been addressed in previous literature.

In this paper we present a Game Theoretic study of the problem of RA in IEEE 802.11 system. Conversely to most of previous literature, we consider WLAN scenarios in which *every* user applies the same RA scheme, independently of the other users. We model the RA process as a strategic game in which the possible strategies are the different PHY modes which can be selected by each user, whereas the goodput achieved by each user is used as payoff for the game. We analyze the aggregate network performance of the Nash Equilibria of the resulting game, showing that there are several conditions in which selfish RA strategies that aim at per-user performance optimization, such as GORA [9], actually converge to a globally worse joint RA strategy than simpler SNR-based solutions. Furthermore, we investigate the possible margin of improvement left for further RA research.

We note that Game Theory has already been proposed for the study of RA problems in CDMA systems [10] and GPRS

GameComm 2009, October 23, 2009 - Pisa, Italy.

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[1] There are actually several implementation issues for which it is not practical to use SNR for RA in IEEE 802.11 systems. Due to this reason, most practical RA algorithms, in particular ARF [4] and its many derivates, are loss-based rather than SNR-based. In this paper, however, we focus on identifying theorically optimal RA strategies, and for this reason we do not consider loss-based RA schemes.

systems [11]. In the context of these wireless technologies, RA is adopted in conjunction with power control; a selfish user would choose a higher transmission power to be able to achieve a higher rate, which would cause an increase in the interference to other users, and which is the key aspect being modeled by the game theoretic formulation. By contrast, in IEEE 802.11 systems a selfish user would choose a lower transmission rate to minimize the need for frame retransmissions; this would degrade the performance of other users due to the increased collision probability[2] and medium access time.[3] Due to this fundamental difference, the model proposed in [10] cannot be adapted to IEEE 802.11 systems. Other game theoretic models target explicitly the 802.11 technology [12–15], but they focus on the modifications of the backoff procedure, and they do not consider the problem of RA. As a consequence, to the best of our knowledge, the study that we present in this paper is novel.

2. SYSTEM MODEL

To analyze the performance of a IEEE 802.11 network we adopt the distance-aware version [16, 17] of the well-known analytical model by Bianchi [18]. We added some further enhancements to this model, in ordert to get from it the performance metrics which are of interest in the RA scenario. The resulting model is summarized in the following.

Let there be N users contending for medium access according to the IEEE 802.11 protocol. Let W be the minimum contention window size, and m be the maximum backoff stage. For each user $i = 1, \ldots, N$ we define:

- τ_i the probability that user i transmits in a given slot, defined as in [18];
- p_i the probability that a frame transmission by user i fails;
- $P_{\mathrm{err},i}$ the probability that a frame transmission by user i fails due to channel impairement;
- $P_{\mathrm{coll},i}$ the probability that a frame transmission by user i fails due to collision with one or more other users' transmissions;
- $T_{s,i}$ the duration of a successful frame transmission performed by user i. In this paper, we consider only basic access mode (no RTS/CTS), so $T_{s,i} = T_{\mathrm{DATA},i} + T_{\mathrm{SIFS}} + T_{\mathrm{ACK},i} + T_{\mathrm{DIFS}}$, where $T_{\mathrm{DATA},i}$ and $T_{\mathrm{ACK},i}$ are defined by the standard and depend on the PHY rate chosen by user i,[4] $T_{\mathrm{DATA},i}$ further depends on the payload size L_i adopted by user i, and both T_{SIFS} and T_{DIFS} are constants defined by the standard;
- $T_{f,i}$ the duration of a failed frame transmission performed by user i. Again, since we consider only basic access mode we have $T_{f,i} = T_{\mathrm{DATA},i} + T_{\mathrm{EIFS}}$, where $T_{\mathrm{DATA},i}$ has been defined previously and T_{EIFS} is a constant defined by the standard.

The model is then defined by the following system of equations:

$$\begin{aligned} P_{\mathrm{coll},i} &= 1 - \prod_{j \neq i} (1 - \tau_j), \qquad \forall i \\ p_i &= P_{\mathrm{coll},i} + P_{\mathrm{err},i} - P_{\mathrm{coll},i} P_{\mathrm{err},i} \qquad (1) \\ \tau_i &= \frac{2(1-2p_i)}{(1-2p_i)(W+1) + p_i W (1 - (2p_i)^m)} \end{aligned}$$

As discussed in [17], the system has a unique solution and can be solved numerically for given values of m, W and $P_{\mathrm{err},i}$ for every user i.

Furthermore, the goodput of user i can be evaluated as

$$G_i = \tau_i (1 - p_i) L_i / \mathcal{T} \qquad (2)$$

where L_i is the payload size of the packets sent by user i, and $\mathcal{T}$ is the average slot time as defined in [18]. A method for calculating $\mathcal{T}$ is provided in [18] for the simple scenario in which the channel is error-free and transmissions by all the users have the same characteristics. However, we could not find in the existing literature a formulation for $\mathcal{T}$ in the type of scenarios considered in [16], i.e., for the case when all the users have different transmission durations and success probabilities. To fill this gap, we propose the following formulation:

$$\mathcal{T} = \sigma P_{\mathrm{idle}} + \mathcal{T}_{\mathrm{succ}} + \mathcal{T}_{\mathrm{err}} + \mathcal{T}_{\mathrm{coll}} \qquad (3)$$

where the different terms are defined below

$$\begin{aligned} P_{\mathrm{idle}} &= \prod_i (1 - \tau_i) \qquad (4) \\ \mathcal{T}_{\mathrm{succ}} &= \sum_i \left(T_{s,i}\, \tau_i (1 - P_{\mathrm{err},i}) \prod_{j \neq i} (1 - \tau_j) \right) \\ \mathcal{T}_{\mathrm{err}} &= \sum_i \left(T_{f,i}\, \tau_i P_{\mathrm{err},i} \prod_{j \neq i} (1 - \tau_j) \right) \\ \mathcal{T}_{\mathrm{coll}} &= \sum_h \left(T_{f,d_h} \tau_{d_h} \prod_{k<h} (1 - \tau_{d_k}) \left(1 - \prod_{k>h} (1 - \tau_{d_k}) \right) \right) \end{aligned}$$

The indices $\{d_k\} \in \mathbb{N}$ reorder the users by decreasing $T_{f,i}$, so that

$$\mathcal{T}_{f,d_k} \geq \mathcal{T}_{f,d_h}, \qquad \forall k < h \qquad (5)$$

This is needed to account for the fact that, when two or more users collide, the duration of the collision is the maximum of the duration of all failed transmissions by the involved users.

To summarize, using (2) we are therefore able to compute the goodput G_i of every user, provided that we know the frame error probability P_{err} and the transmission durations T_s and T_f which belong to every user. Assuming that all the users adopt the same fixed payload size $L_i = L$, the values $T_{s,i}$ and $T_{f,i}$ will depend exclusively on the PHY mode chosen by the user i; furthermore, the value of $P_{\mathrm{err},i}$ will depend on both the PHY mode chosen by the user i, and the Signal-to-Noise Ratio (SNR) experienced by that user.

With these considerations in mind, if we look at (1), (2), (3) and (4) it is evident that the performance of each single user depends not only on the PHY mode it chooses,

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[2] This is due to the binary exponential backoff procedure of 802.11: the less are the chances that frame transmission by a given stations fail, the higher will be the chances that the same station will transmit at a random slot, and consequently the higher will be the collision probability perceived by other stations.

[3] This is due to the fact that in 802.11 a station freezes its backoff counter whenever it is detected that another station is transmitting.

[4] we assume that the ACK is always sent at the same PHY rate of the DATA packet

but also on the PHY mode selected by every other user. In other words, the choice of the rate performed by any user affects the performance of all remaining users. It is therefore convenient to model the rate adaptation problem as a strategic game in which the strategy of each player is given by the possible PHY modes he can select. In this paper, we consider that each user i can choose a strategy $S_i \in \{6, 12, 18, 24, 36, 48, 54\}$. The label of each strategy refers to the data rate in Mbps of the corresponding IEEE 802.11g PHY mode. We included all 802.11g DSSS-OFDM modes, with the exception of the 9 Mbps mode, whose performance is known to be dominated by that of the 12 Mbps mode under all conditions, as discussed in [9] and evident from Figure 1.

For the payoff function of each user i, we choose its goodput. That is, every single user will choose the rate strategy that maximizes his expected goodput, with respect to the joint strategy S_{-i} played by the other players. Apart from some practical implementation issues, this rate adaptation strategy is the one adopted by GORA [9]. Therefore, the analysis of the strategic game we just described will provide us with an interesting insight in the behavior of GORA in a scenario where it is adopted by all users in the network. This is interesting since previous work only considered scenarios in which only one user was adopting GORA, and where other users were using legacy rate adaptation techniques, such as MBLAS or ARF. In those scenarios, the target station using GORA experienced significantly better performance than the other non-GORA stations. However, in the following section will show that such a performance gain disappears when all the users adopt GORA.

3. PERFORMANCE EVALUATION

We want to determine the Nash Equilibria of the rate adaptation game that we described in the previous section, in order to be able to evaluate to what joint strategy GORA converges. Unfortunately, since we are using (2) as the expression for the payoff of each player, there is no straigtforward way to solve the game in a closed form. In fact, in order to evaluate (2) for a given joint strategy, the system of equations (1) needs to be solved numerically for that joint strategy. For this reason we could not find any method to determine Nash Equilibria analytically, nor to guarantee their existance. It is to be noted that an approach to derive a closed-form expression of the payoff from the Bianchi model, on which (2) is based, can be found in [14] for contention window control games; however, this approach is based on an erroneous interpretation of the Bianchi model, and therefore does not yield a correct expression of the payoff.[5]

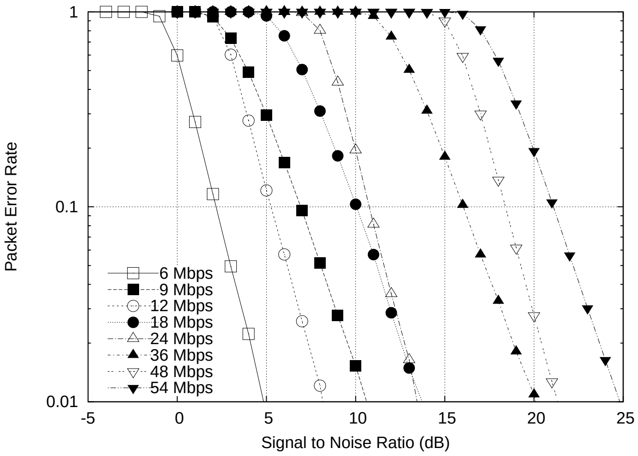

Figure 1: The chosen model for the Packet Error Rate performance versus Signal to Noise ratio of the IEEE 802.11g PHY modes

To overcome this issue, we resorted to numerical methods for the determination of Nash Equilibria in particular instances of the RA game. For this purpose, we used `gambit` [19], which is an open source software for Game Theory; in particular, we used the tool `gambit-enumpure`, which implements an algorithm for the search of pure strategy Nash Equilibria.

The goodput model of (2) was implemented in `octave`. For each of the strategies (i.e., PHY modes) available to the players, we determined the values of $T_{s,i}$ and $T_{f,i}$ according to the IEEE standard; a fixed payload size $L_i = L =$ 1000 bytes was used for all users. The values of $P_{\mathrm{err},i}$ were calculated for this payload size using the same Packet Error Rate model adopted in [9]; the resulting Packet Error Rate is reported in Figure 1 as a function of the SNR. With this configuration, a particular instance of a RA game is uniquely identified by the number of users and by the SNR value experienced by each user.

We recall that the objective of this study is to investigate the behavior of selfish congestion-optimized RA schemes such as GORA by analyzing to what Nash Equilibria they converge. Furthermore, we want to compare this behavior with that of legacy SNR-based RA schemes, and also to understand what is the possible margin of improvement left for further RA research. In order to do this, we need to find a method to evaluate the performance of a joint RA strategy in a global sense, rather than from the perspective of a single user. For this purpose, we consider two additional performance metrics. The first one is the aggregate throughput A, defined as

$$A = \sum_{i=1}^{N} G_i \tag{6}$$

and the second one is Jain's fairness index F [20] of the throughput performance, defined as

$$F = \frac{(\sum_{i=1}^{n} G_i)^2}{N \sum_{i=1}^{N} (G_i)^2} \tag{7}$$

which assumes a maximum value of 1 when all users have the same throughput, and a minimum value of $1/N$ when only one user has a positive throughput and all other users have

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[5] In detail, the authors of [14] interpret the Bianchi model as a single equation providing the collision probability of a given user as a function of the transmission probability of all the other users; however, the Bianchi model is actually a system of equations whose solution determines both the collision probabilities and the transmission probabilities [16–18]. As a consequence of this misinterpretation, the authors of [14] derive a model based on the assumption that, when a given user unilaterally changes its Contention Window (CW) strategy, the transmission probabilities of the other users will not vary. In reality, however, the change in the CW strategy by the given user will cause a change in the transmission probabilities of the other users even if they stick with the same CW strategy.

null throughput. Since we deal with a scenario in which, in general, each user has a different SNR, it might appear rather counterintuitive that F is defined over the goodput performance of every user, and not normalized, e.g., by the channel capacity of each user as determined by its SNR. The fact is that, due to the way the IEEE 802.11 standard works, when users adopt the same payload size and choose the PHY rate that yields a reasonably low packet error rate, then all users experience a throughput performance which is quantitatively similar, in spite of the differences in the PHY rate. This fact, which was first observed in [21], is evident from (1) when we recall that, if $P_{\mathrm{err},i} \to 0\,\forall i$, then $p_i \to p$ and $\tau_i \to \tau\ \forall i$, i.e., the transmission and collision probabilities of all users tend to the same values.

To compare the performance of GORA with that of legacy SNR-based strategies, for every RA game instance we also determine the (unique) joint strategy that is given by the MBLAS RA algorithm [1]. According to MBLAS, every station selects the PHY rate to be used as a function of its SNR only, without taking into consideration the behavior of other users. We chose MBLAS over other SNR-based RA strategies (such as, for instance, RBAR [2]) because it is the best performing scheme in this category.

Furthermore, to have an idea of how much GORA and MBLAS are close to the performance of an ideal joint RA strategy, we define two other joint strategies. The first one is called Best Aggregate Throughput (BAT), and it consists of choosing the strategy that maximizes the aggregated throughput A by doing an exhaustive search over all possible joint strategies for a given game. The second one is called Best Aggregate Throughput with Constrained Fairness (BAT-CF), and consists in choosing the strategy that maximizes A while satisfying $F \geq \overline{F}$, where $\overline{F} \in [0, 1]$ is a target fixed value for the minimum admissible fairness. The reason why we defined the BAT-CF strategy is that the BAT strategy often results in the starvation of users with low SNR to favour users with higher SNR that can successfully use higher data rates and consequently provide more significant contributions to the aggregate throughput; with this respect, guaranteeing a minimum value of the fairness metric F can effectively prevent starvation.

Finally, we note that only GORA and MBLAS can be implemented in real devices [1, 9]; on the contrary, BAT and BAT-CF, while convenient in our study for peformance comparison purposes, are not practical for implementation, since in real 802.11 networks it is not possible for a single user to know the expected goodput performance of other users for all possible joint RA strategies.

In the remainder of this section, we will use the performance evaluation methodology just described to evaluate some practical 802.11 RA scenarios.

3.1 Scenario 1: all users with equal SNR

In this scenario, all users experience the same SNR. We evaluate different games, each for a particular value of the SNR and of the number of users N.

The resulting performance is reported in Figures 2–5. In most game instances, GORA has a single Nash Equilibrium; however, for a few values of SNR there are more than one Nash Equilibria. In this last case, we report the performance for each equilibrium point; in the figures, this is easily recognized by the fact that more than one value is reported for the same SNR value (e.g., Fig. 3, SNR=6 dB).

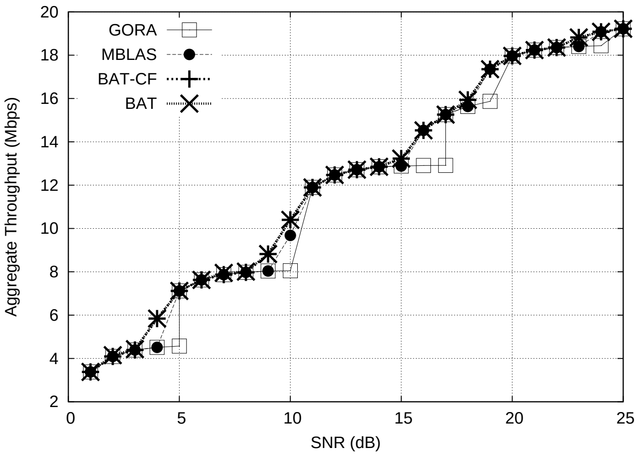

Figure 2: Aggregate Throughput A for different RA strategies in a scenario with $N = 2$ users with equal SNR

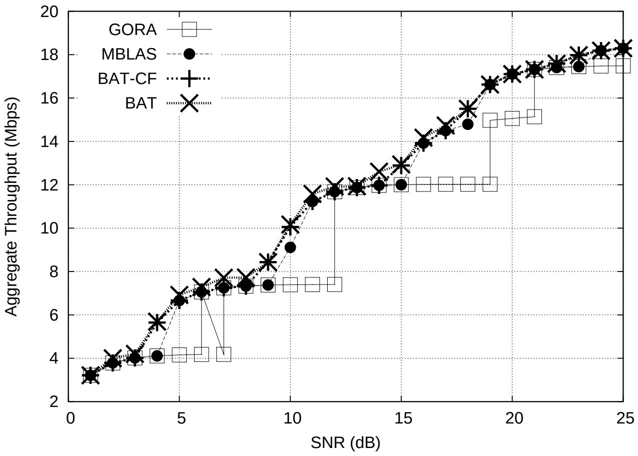

Figure 3: Aggregate Throughput A for different RA strategies in a scenario with $N = 5$ users with equal SNR

From Figures 2 and 3, it is evident that for several values of the SNR the aggregate throughput performance of the Nash Equilibria of GORA is not only inferior to both BAT and BAT-CF, but is also worse than the legacy MBLAS rate adaptation strategy. As for the fairness, reported in Figures 4 and 5, we note that BAT often provides a significantly unfair joint strategy, whereas BAT-CF is able to provide almost the same aggregate throughput without any degradation in fairness. The particular value of $F = 1$ which occurs always for MBLAS, GORA and BAT-CF is due to the fact that in this scenario all users have the same SNR, and so they will get exactly the same goodput performance whenever they choose all the same PHY mode.

To better explain the types of behavior observed in this scenario, we analyze more in detail the two-user games for SNR $\in \{3, 4, 5\}$; these games are represented in Figures 6, 7 and 8, respectively. In these figures, we omit all those user strategies which have a zero payoff for all the strategies chosen by the other user.

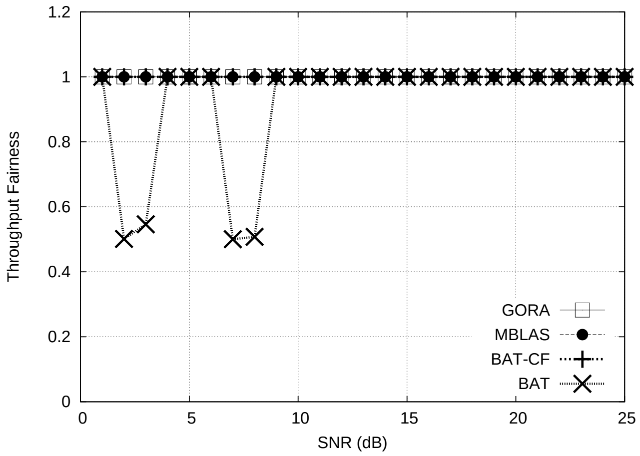

Figure 4: Fairness index F for different RA strategies in a scenario with $N = 2$ users with equal SNR

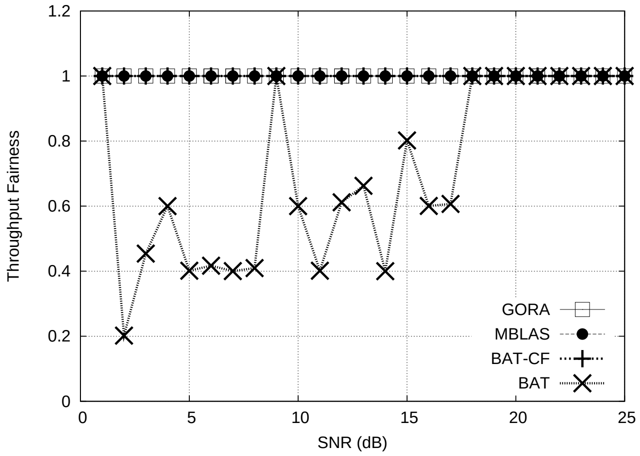

Figure 5: Fairness index F for different RA strategies in a scenario with $N = 5$ users with equal SNR

		user 2	
		6 Mbps	12 Mbps
user 1	6 Mbps	2.195, 2.195	4.232, 0.197
	12 Mbps	0.197, 4.232	1.370, 1.370

Figure 6: Two-user Rate Adaptation Game where both users have SNR= 3 dB

		user 2		
		6 Mbps	12 Mbps	18 Mbps
user 1	6 Mbps	2.255, 2.255	3.494, 1.330	4.641, 0.000
	12 Mbps	1.330, 3.494	2.920, 2.920	5.649, 0.000
	18 Mbps	0.000, 4.641	0.000, 5.649	0.001, 0.001

Figure 7: Two-user Rate Adaptation Game where both users have SNR= 4 dB

		user 2		
		6 Mbps	12 Mbps	18 Mbps
user 1	6 Mbps	2.286, 2.286	3.104, 2.214	4.701, 0.004
	12 Mbps	2.214, 3.104	3.558, 3.558	7.073, 0.008
	18 Mbps	0.004, 4.701	0.008, 7.073	0.075, 0.075

Figure 8: Two-user Rate Adaptation Game where both users have SNR= 5 dB

For the game with SNR= 3 dB (Figure 6), the most desirable joint strategy for the whole network is clearly $\{6, 6\}$. GORA, MBLAS and BAT-CF all successfully select this strategy. BAT, on the other hand, selects either $\{6, 12\}$ or $\{12, 6\}$, due to the greater aggregate throughput performance obtained (4.4290 Mbps instead of the 4.3900 Mbps obtained with $\{6, 6\}$); unfortunately, the price of this slight increase in aggregate throughput is a significantly unfair joint strategy.

In the game for SNR= 4 dB (Figure 7), we see an instance of the well-known Prisoners' Dilemma. The most desirable joint strategy for the performance of the whole network is $\{12, 12\}$; however, both players increase their payoff if they deviate from this strategy, and the only Nash Equilibrium of the game is $\{6, 6\}$, which yields inferior payoff for both players, and consequently a sub-optimal aggregate throughput. This type of behavior is the most frequent reason that causes GORA to perform worse than all other schemes for several values of SNR.

Also for the case that SNR= 5 dB (Figure 8) the most desirable strategy is $\{12, 12\}$; however, in this case GORA has two Nash Equilibria, i.e., $\{6, 6\}$ and $\{12, 12\}$. Practical implementations of GORA [9] rely on goodput estimation techniques which are affected by time-varying random estimation errors. This means that, in real systems, GORA could oscillate between Nash Equilibria, depending on how stable is each equilibrium point (i.e., depending on the difference in payoff between the equilibrium point and adjacent joint strategies). As a consequence, on average GORA will experience an inferior performance with respect to the other schemes.

3.2 Scenario 2: users uniformly distributed in a square area

This scenario is representative of real IEEE 802.11 network deployments. Users are uniformly distributed in a square area with a side of 20 m, and they all communicate with the Access Point located in one corner of the square. To evaluate the SNR perceived by each user, we use a log-distance propagation model [22] with a pathloss exponent value of 3 and a reference SNR value of 35.351 dB at a distance of 2 m. For each value of $N \in \{2, \ldots, 6\}$, we evaluated 100 randomly generated RA games, and averaged the performance obtained with the MBLAS, BAT and BAT-CF strategies over all games. For GORA, we first averaged the performance over all Nash Equilibria in the same game, and then averaged the resulting values over all games.

The resulting performance is reported in Figures 9 and 10. We observe that GORA performs significantly worse that MBLAS, and that the performance gap in general increases with the number of users. BAT achieves an aggregate throughput which is significantly greater than that obtained by all other schemes; however, this comes at the price of an unacceptably unfairness. On the other hand, the BAT-CF strategy is effective in providing fairness, but on average its aggregate throughput improvement over MBLAS is almost negligible.

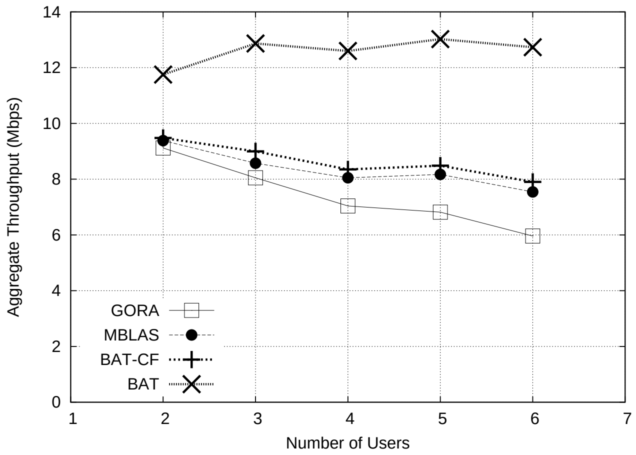

Figure 9: Aggregate Throughput performance of different RA strategies when users are uniformly distributed in a 20×20 m area

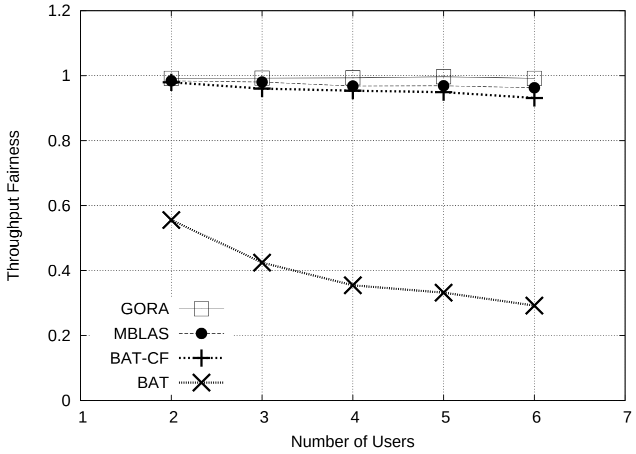

Figure 10: Throughput fairness of different RA strategies when users are uniformly distributed in a 20×20 m area

4. CONCLUSIONS

We analyzed the problem of Rate Adaptation (RA) in IEEE 802.11 based Wireless LANs by means of a Game Theoretic approach. Our performance evaluation showed that medium-access aware RA strategies such as GORA, in which every station attempts to selfishly maximize its goodput, actually result in a degradation of the overall network performance. On the other hand, simple legacy RA techniques such as MBLAS, in which every station chooses the PHY rate based solely on its Signal to Noise ratio, are much more robust and, on average, result in better performance. Finally, the comparison of MBLAS with globally optimal joint RA strategies showed that the margin for improving the aggregate throughput performance while maintaining a satisfactory degree of fairness among users is actually rather small.

5. ACKNOWLEDGEMENTS

This work was supported in part by the Spanish Ministry of Science and Innovation under grant number TEC2008-06826/TEC (project ARTICO) and by the European Commission in the framework of the FP7 Network of Excellence in Wireless COMmunications NEWCOM++ (contract n. 216715).

This work is dedicated to the memory of Federico Maguolo.

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