# COOPERATIVE AND SELFISH BEHAVIOR IN UNLICENSED SPECTRUM USING THE CSMA/CA PROTOCOL

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## ABSTRACT

It can be shown that in a communication system which uses CSMA/CA for medium access control greedy behavior can be discouraged by punishing the greedy users. However in a real system it is not always possible to punish a misbehaving user. Actually numerical experiments show that it is difficult to achieve enough punishment do discourage greediness since it takes time to detect that a user misbehaves and the time that a user can be punished is limited.

## I. BACKGROUND

Lately we have seen an increase in the use of unlicensed spectrum. The success of the IEEE 802.11 suite of standards and the success in the marketplace cannot be disputed. Today there are also numerous hotspot providers that provide high speed internet access in for example airports, cafés and fast food restaurants. The traditional telecom operators are also embracing this technology as a complement to their mobile service offerings. Something that can be seen both from those who actually operates hotspots and the high interest in 3G and WLAN interworking.

But as the use of spectrum increases the interference caused by the users in this band also increases. At some point the interference becomes a problem and devices must be able to cope with that. However as usage increases even further the interference cannot be handled and the capacity of the system is reached.

There are numerous techniques for handling interference. Either the interference can be avoided. Examples of this philosophy are automatic channel allocation or the CSMA/CA protocol where one waits for the channel to be empty before transmitting. The other philosophy is to simply live with the interference. By introducing some redundancy the message will eventually get through even though some bits are lost. Slow frequency hopping, DS-CDMA and coding and interleaving techniques are examples of this approach.

Most of these techniques have been developed and/or evaluated in a setting where the aim is to avoid manual configuration or to add dynamic behavior to a system. A lot about this can be found in the literature, but they all assume that all users in the system share a common objective (maximizing system capacity) set by the system designer. What is unique with unlicensed spectrum is that there are many users of the spectrum that may not share the same objective. Many times the users are only interested in maximizing their own performance. The designers of the IEEE 802.11b standard were able to make all the users share the same common goal by making the standard in a specific way. For a single user deviating from this common goal is difficult. Modifying equipment is beyond the reach of most users and most products implement the resource sharing algorithm in the same way. But as the market matures it is increasingly important to show good performance and is easy to imagine that manufacturer X add proprietary “features” that enhance the performance at the expense of other equipment not made by manufacturer X. There already examples of this happening [1].

## II. PROBLEM

The problem is to find rules that ensure a good cooperation. The spectrum regulators are interested in maximizing spectrum usage effectiveness while not limiting the possibilities for innovation and economic growth. (They do have an easy task, don’t they?). Determining which rules that achieve these goals is difficult. However there are some general observations. By creating a large set of rules that users must follow it is possible to make all the users behave like one system and thus maximize capacity. More rules usually mean that it is harder to control that they are followed. But maybe the most troublesome is that a lot of rules tend to limit the possibilities for innovation. At the extreme there can only be one specific service from one specific manufacturer.

To find the best set of rules we must be able to evaluate them. The problem is to find out what performance can be expected if users act selfishly under specific rules. This type of problems can be analyzed using game theory.

Using game theory we model a radio system by letting the individual users be actors that try to maximize their utility. To do that each user has a number of actions called strategies that he can take. Depending on the actions that the various users take they will have a different payoff, e.g. average throughput.

In this paper we investigate how different strategies influence the performance of users in a wireless network using CSMA/CA as contention scheme.

There is one important difference between games that are played only once and games that are repeated many times. The difference is that in games that are played only once the users have no incentive to cooperate but in repeated games there is the possibility for a user to punish the other users. This property tends to encourage cooperation.

It can be shown that in a CSMA/CA game that is played only once the best strategy is to start transmitting immediately, something that of course causes the system to break down completely. However when the game is played repeatedly cooperating users can punish the misbehaving user and it is possible to reach an equilibrium point [2].

One of the assumptions done when analyzing repeated games is that the game is played infinitely. If the game is played a limited number of times the last game will be equivalent to a game played only once [3]. The reasoning is that it makes sense to not cooperate the last time. However the same argument can be recursively applied to all games and thus some of the results of the analysis become invalid.

In a radio system where users move around the time one user can punish another user is limited since they will eventually move so far apart that they cannot interfere with each other. Game theoretic studies of games played and infinite time obviously ignores this. Also most studies disregard the capture effects, i.e. the transmitter and receiver are so close that it is not possible to interfere with the signals, i.e. punish a user.

In this paper we investigate the possible gains that can be obtained by cheating in a radio environment. The evaluation is carried out by numerical experiments where we let a number of users utilize different strategies and determine the performance.

## III. MODELS AND ASSUMPTIONS

The relative successfulness of the various strategies have been evaluated using numerical experiments. The propagation and mobility parameters have been borrowed from macro-cellular systems. The reason is simply that these models were readily available and already implemented in MATLAB in the RUNE toolbox [5]. However the effects of the various strategies of the users should be similar in other environments.

The system consists of total 64 cells. We assume that there are 4 channels available which results in 16 cells per channel. To avoid border effects we use a wraparound technique to create a borderless surface to place the system on. The system is planned using a regular channel plan. The propagation is modeled using the Okumura-Hata model, i.e. the propagation loss can be described as: $L=28+35\log(R)+X$ [dB] where X is a random variable with mean 0 and standard deviation 8 dB. The cell radius is 1000m. The transmitter power is 1 W and the noise is set to result in a median SIR at the cell border of 25 dB. Thus the system is essentially interference limited.

There are on average three users per access point. The average mobile speed is 15 m/s which results in a median staying time in each cell of 6.5 seconds. The mobility model is further explained in [5]. The handoff margin used is 3 dB and no handoff is performed when a user is transmitting a packet.

We study the full traffic case. I.e. all users always have packets to send. To be able to study how the strategies influence throughput we only have traffic from the users to the access point. It is not reasonable to assume that the access-points will have different strategies for different users.

For programming convenience the system is implemented as a slotted system. Each slot is 20 ms and each packet is 10 slots. This gives a user time for transmitting approximately 30 packets while in a cell.

To be correctly received the SIR for all slots in a packet have to be above 10 dB. A channel is considered to be free if the received signal level not more than 5 dB above the noise level. Feedback information is assumed to be instantaneous and error free.

## IV. STRATEGIES

Strategies are randomly assigned to the users. No user switches strategies during the numerical experiments. In the system there are three different strategies that a user can follow.

The first is the greedy strategy. The user starts to transmit a packet as soon as it has finished the previous packet. If the other users are timid and listens before speaking, this strategy will essentially give the greedy user the full access to the bandwidth. However if all users implement the greedy strategy this is obviously not a good strategy since all users will interfere with each other.

The second strategy is to use a CSMA/CA protocol. The protocol implemented by these users is very similar to the protocol used by devices implementing IEEE 802.11 [4]. Whenever a user has finished transmitting a packet he draws a random number on the interval [0,FW]. The user then waits for this number of empty slots before transmitting the next packet. If there is someone else transmitting on the channel the counting down is suspended. If the packet is lost on the way the FW variable is doubled. If the packet is successfully transmitted the FW is reset to the initial value. The minimum FW value is set to 8 and the maximum is 256.

The player strategy users follow the timid strategy initially. However if they detect that another user is behaving in a greedy fashion they can punish that user. Detecting that a user is cheating is non-trivial. In the paper written by Cagalj et al [2] it is suggested that each user measure the throughput of all the other users and deem a user to be cheating when that user achieves a higher throughput than the rest of the users. In this paper we use a slightly simpler algorithm. The user that transmits 5 packets in a row without releasing the channel is considered to be greedy. Punishing a user is done by deliberately jamming a packet sent by the user. The user is punished for 5 packet times. We assume that this can be done since the packet header contains the address of the sender and thus it is possible to quickly determine which packets are sent by a specific user. If a user moves into another cell the punishment is stopped immediately. It is not possible to punish a user if he is on another channel or in another cell.

## V. RESULTS

In all numerical experiment we simulate 400 seconds. The median staying time in a cell is approximately 330 slots or 6.6 seconds. The throughput per user is measured as the fraction of slots that a user sends useful data. In an ideal situation with only timid users they would achieve a throughput of 33% each. But in our experiments it is slightly less. Handoffs, hidden terminals and contention times all reduce the throughput.

In the first experiment we have 10% greedy users and the rest are timid users. In fig. 1 we can see that there is a substantial gain for the greedy users. Note that even the timid users get some data through. The reason is that in some instances there are no greedy users in a specific cell and thus they can get some packets through.

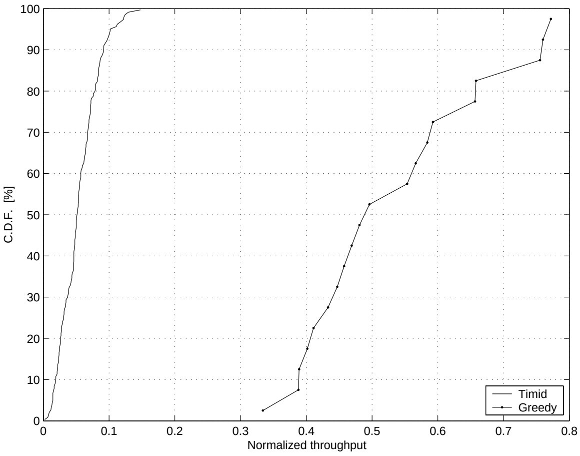

*Figure 1 – In a system with only timid users and only a few greedy users the performance improvement for the greedy users is substantial.*

If we increase the number of greedy users to 80% we can see (in fig 2) that the throughput drops for all users. One thing to note though is that there is actually some data that gets through for both categories of users.

There are two effects that cause this. There is a probability on the order of 0.1-0.2 that there is only one user in a cell. The second reason is the capture effects. If a user is sufficiently close to the access point the SIR is acceptable even though there is a lot of interference on the channel.

In the third experiment we introduce users that follow the "player" strategy, i.e. they are able to punish users that hog the channel too long. In fig. 3 we can see the results of an experiment with 30% players and 10% greedy users.

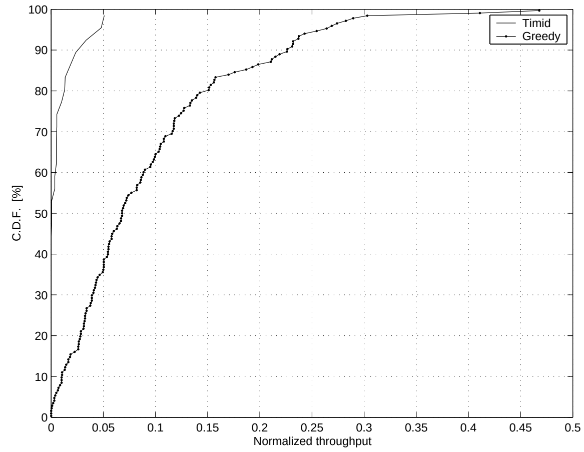

*Figure 2 – In a system with only greedy users only a very limited throughput is achieved.*

It can be seen that the "player" users achieve approximately the same performance as the timid users. This is no surprise since they use the same channel access method as the timid users. However we note that there is a drop in the performance of the greedy users. But even though the performance drops there is still a significant gain in being greedy.

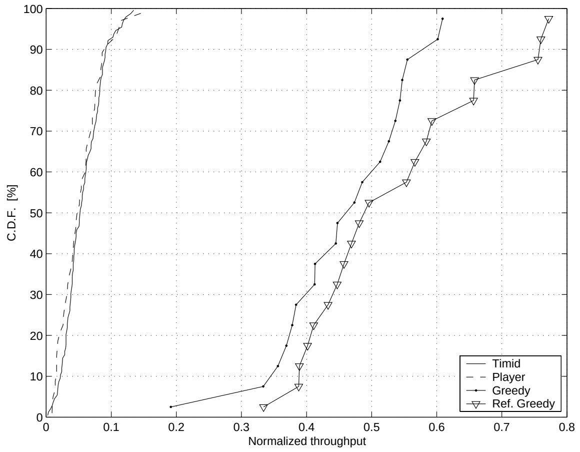

*Figure 3 – In a system with 30% "player" users and 10% greedy users the greedy users just get a marginal degradation of their performance.*

In the fourth experiment 90% of the users follow the "player" strategy and 10% of the users are greedy. In figure 4 we can see that there is a slight degradation in performance for the users that are greedy. However there is still a large discrepancy in the performance of the "player" users and the greedy users. In the equilibrium case the players would punish the greedy users so that they get their performance reduced to that of the "player" users. There are many reasons for this behavior. The first is the detection process. In our experiments it takes some time before it is detected that a user is cheating, during that time the greedy user essentially gets full use of the channel. The second is that the punishment may not be severe enough. In our experiments it is only a fixed number of packets that are erased for the greedy user. It should probably be more appropriate to reduce the throughput of the greedy user to the level of throughput that the "player" user experiences. The third reason is that it may not always be possible to punish a greedy user because of capture effects.

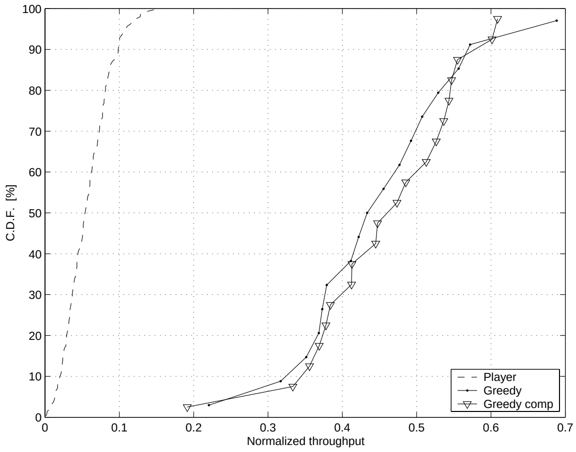

*Figure 4 – Throughput for a system with 90% player users and 10% greedy users. In the graph the results for the greedy users from fig 3 are included for reference.*

## VI. DISCUSSION

The main outcome of this study is that we have shown that it is actually difficult to implement punishment in a radio system. This is discouraging since finding a cooperative solution generally requires the ability to punish the other users. Users are behaving in a non-greedy fashion otherwise they will be punished. If that incentive goes away then all users will behave greedily and the system will break down.

In the system we have studied it seems like the possibilities to punish are limited. In order to be effective the throughput of the misbehaving users should be reduced to below the throughput of the "player" users. One of the obvious problems is that of detecting that a user actually behaves in a greedy way. It takes some time to do that and during that time the greedy user is rewarded.

Once we have detected that a user is greedy he can only be punished as long as he stays within the cell. It is of course possible to imagine that the user is followed to the next cell and that the well behaved users tell the users in the next cell to "watch out for this guy". However that is well beyond the scope of this paper. In the numerical experiments the punishment mechanism is quite simple. However it is possible that the time a user stays in a cell is too short to allow for effective punishment.

There are also capture effects. I.e. sometimes a greedy user may be out of reach of punishment. It is difficult to judge the influence the effect on the results and further analysis is needed. The net result is that it may pay off for a user to behave in a greedy way. He may be prepared to take some punishment since the reward for behaving greedily is large.

The assumptions made here about user mobility may be slightly pessimistic. Currently unlicensed systems are mainly used where the users move at a pedestrian speed at most, on the other hand the cells are smaller. In a system where users stay longer in a cell it is easier to punish a misbehaving user.

The mechanisms for detection and punishment are quite simple. With more sophisticated techniques it may be easier to detect when a user is greedy and administer punishment in a proportional fashion. On the other hand the greedy users in our experiments are easy to detect more complicated strategies for cheating may take longer to detect. Another thing that can be changed is that the greedy users do not give up the channel when they detect that they are being interfered with, they should do that in order to make the other users stop punishing them. On the other hand there seems to be no gains in giving up the channel.

## VII. CONCLUSIONS

The results indicate that it is indeed beneficial to be more aggressive than the equilibrium strategy would suggest. In the equilibrium strategy all users behave like timid users. The reason is mainly that it takes time to detect that a user behaves greedily and that the possibilities for punishing him is limited, either because of the capture effects or because he leaves the cell shortly.

## REFERENCES

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