

Coopetition – practical methodology for efficient sharing of radio resources in wireless networks

Marcin Parzy
Chair of Wireless Communications
Poznan University of Technology
ul. Polanka 3
61-635 Poznan, Poland
mparzy@et.put.poznan.pl

Hanna Bogucka
Chair of Wireless Communications
Poznan University of Technology
ul. Polanka 3
61-635 Poznan, Poland
hbogucka@et.put.poznan.pl

ABSTRACT

In this paper, we present the idea of resource allocation using the coopetition methodology, which combines the advantages of both cooperative and competitive approaches. This idea is known from economics, as well as in some other fields, e.g. in the complex production and management systems. We show that the problem of radio resource allocation in wireless systems can be solved efficiently by using coopetition. We define new complete methodology, describe possible tools which can be used at each stage and present examples illustrating a new framework. Simulation results are also provided.

Keywords

Game theory, coopetition, cooperation, competition, OFDMA, radio resource allocation.

1. INTRODUCTION

In contemporary wireless communication there are two trends which are conflicting each other. On one hand, there are increasing demands from users and telecommunication operators concerning the spectrum resources and the associated Quality of Service (QoS) levels. This trend is determined by mobile users requesting unlimited access to mobile Internet multimedia services virtually any time and anywhere with their portable equipment. On the other hand the amount of the existing and available spectrum resources remains stable or is shrinking over a long period of time.

Due to the scarcity of spectrum resources there are a few methods of improving the existing situation. Firstly, new algorithms of radio resource management are being developed, which face two major efficiency problems: they can be spectrally efficient and provide fairness of resource distribution but either they are centralized and require management infrastructure or they are distributed and require a significant amount of control traffic. Apart from the radio resource management, another option to utilize the available spectrum in an efficient manner is to use adaptive transmission techniques, e.g. link adaptation with the

objective to maximize the link throughput.

A very promising option is to increase the spectrum supply by browsing the spectrum opportunities, called spectrum gaps or holes. These gaps are locations on the frequency axis at which the spectrum resources are not used in a given area at a given moment. They can be used in an opportunistic way for example to organize local networks or peer-to-peer communications. It is apparent that this information about unused spectrum must be gathered in some way. It is envisioned that future cognitive radio devices will be able to gather the knowledge of their radio environment. This may be done by spectrum sensing or by accessing the geo-location spectrum database. After getting that knowledge all cognitive radios may be able to decide about the usage of the available spectrum, resource allocation, parameters of transmission etc., provided that they do not cause interference to existing licensed systems nor to each other.

There are many activities concerning opportunistic spectrum access and cognitive radio which are carried out world-wide. Their goal is to define new framework for efficient dynamic spectrum sharing in different areas. As an example, in the COGEU project (COGNITIVE radio systems for efficient sharing of TV white spaces in European context) the possibility of using TV white spaces is being examined. The players of the secondary spectrum market can be the infrastructural telecommunication operators, but the participation of the cognitive radios is also envisioned. In scientific communities concentrated around European networks, e.g. ACROPOLIS (Advanced coexistence technologies for radio optimization in licensed and unlicensed spectrum) or COST Action IC0902 ("Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks") new frameworks for spectrum sharing of cognitive radios are being proposed and developed.

In this paper, we also aim at defining the new methodology for practical and efficient opportunistic spectrum access and the spectrum allocation to multiple cognitive radio networks competing for these resources. For this purpose, we bring the idea of coopetition which combines the advantages of cooperative and competitive games that can be defined for our problem formulation. Coopetition approach was successfully used as a framework in some research areas such as cybernetics, control of complex systems and in economics. We postulate to use coopetition as a methodological framework also in wireless telecommunication for resource allocation in the systems, which use orthogonal frequency channels for multiplexing users' access to the network, e.g. Orthogonal Frequency Division Multiple Access (OFDMA) systems. We consider cognitive radios as

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

GAMECOMM 2011, May 16, Paris, France
Copyright © 2011 ICST 978-1-936968-09-1
DOI 10.4108/icst.valuetools.2011.245833

players, which are interested in accessing the spectrum holes and in making the best use of the available resources in order to maximize their throughput.

The paper is organized as follows. In section 2 the definition of coopetition is recalled as well as its existing applications are presented. In section 3, a new concept of using coopetition as a methodology for spectrum sharing is being presented. In section 4 numerical examples are presented. Conclusions may be found in section 5.

2. COOPETITION AND ITS APPLICATIONS IN ECONOMY

Coopetition is a neologism combining the notion of cooperation and competition. Originally coopetition was defined in [1]. This reference describes and explains the idea of combination of cooperation and competition. Coopetition approach is based on the fact that cooperation creates an added value to the resulting product (outcome) of this cooperation and that this added value can be distributed among competitors who have previously created it. According to definition given in [2], coopetition is the behavior of two or more competitors cooperating in some areas of their usual activities or business. It may be driven by the company cost reduction or any other goal which can help all competitors. An example given in [2] is the cooperation arrangement between Citroen, Peugeot and Toyota to work together on some components which were used in their cars (Citroen C1, Peugeot and Toyota Aygo), although on the car-market they have remained competitors. The involved companies were able to reduce their production costs taking advantage of sharing of some part of their common cost. In classic competitive approach each of those three companies would have to pay the whole common cost thus reducing their profit than in case of coopetition.

Another example of coopetition has been presented in [3], where the authors present coopetition in development of mobile TV. An added value created is a complete product which combines Internet, TV and telecommunication network (telephony Internet, mobile TV). In the coopetition mode, the broadcasting and telecommunication companies maintain a high level of cooperation and competition. Although there are different TV operators, the infrastructure and technical solutions are common, what creates the opportunity for cooperation between them. From the authors' perspective, the coopetition is the only way of successful development of mobile TV.

Coopetition was also considered in [4]. The author considered cooperation and the constructive conflict as positive mechanisms in the supply chains, in knowledge sharing, and beyond. Coopetition there is described as a partnership of companies. The author noted that firms can generate extra profit thanks to coopetition balancing cooperation and competition between each other, and can be carried out between companies to achieve common goals and solving conflicts. A conflict (or competition) can be constructive when it leads to finding resolution, e.g. as in the discussion or bargaining.

An example of coopetition presented in [5] aims at solving marked-based scheduling problem which was the alignment of the producers' outputs and the consumers' demands according to the demands deadlines and the producers' capabilities of serving each demand. The concept of intelligent agents sending bids to each

other has been used. Producer agents use coopetition which is simultaneously cooperation and competition with other agents. The allocation problem has been defined as an optimization problem so the protocols known from cooperative and non-cooperative game theory were applied.

Another example of coopetition between two ports (in Shenzhen and in Hong Kong) is presented in the series of papers especially in [6], [7], [8] and in [9]. In [6] the authors explain why the coopetition between those two ports is the best option and why it should be implemented. A game model based on Analytic Hierarchy Process (AHP) is presented and the result of that game proved that coopetition assures the highest benefits of both ports.

In [7] static Bertrand game with complete information between those two ports has been presented. The following actions between players have been considered: competition - competition, competition - cooperation, cooperation - competition, cooperation - cooperation. When the player was playing competition only his profit was maximized, when the player played cooperation, joint profit of both players was maximized. The authors analyzed the influence of game parameters on the final players' strategies. For some particular parameters competition chosen by both players resulted in the highest profit for both of them, however, for some other parameter values it has been proven that coopetition has been the most profitable.

In [8], coopetition was introduced as one of the most optimal strategies in situations with price competition. The other ones considered in that paper were: service differentiation and cost-leadership strategy. The difference between the game model applying coopetition and the one not applying it was in the definition of the profit (payoff) function which was different for the players in the game model without coopetition and common in the model with coopetition. After comparison coopetition was accepted as an option which allows avoiding direct competition and lower payoff.

Bertrand game as a model of game between the abovementioned two ports was further considered in [9]. The authors applied the evolutionary game methods (evolutionary stable strategy – ESS) and proved that a long term equilibrium in this game may be (is dependent on parameters of the game) complete cooperation (both players cooperate) or complete competition (both players compete).

More about coopetition can be also found in [10], [11], [12] and in [13]. Coopetition was also applied for multimedia resource allocation in [14].

The only example of coopetition considered for wireless communications has been presented in [15]. The authors used coopetition for power allocation in the game of two users sharing the same frequency channel. The competition between two users (Stackelberg duopoly) was translated into the cooperative competition. The authors show that coopetition may be beneficial for both users.

3. COOPETITION IN RADIO RESOURCE ALLOCATION

3.1 General description

In the previous chapter we shortly overviewed application of cooperation in economics, production systems and logistics. Let us now consider application of this idea to spectrum sharing between wireless devices competing for available resources.

Existing algorithms for radio resource allocation apply either cooperative games with complete information or non-cooperative games with incomplete information. The proposed solutions are thus centralized or distributed. The main problem in distributed wireless networks is usually the lack of the channel state information (CSI) of all involved players. Each user usually knows only her own CSI. In centralized systems the central element usually knows the CSI of each user, and for these systems classical resource management techniques may be applied, such as MaxSNR, Round Robin, Proportional Fairness, presented in [16], or multiuser water-filling algorithm [17].

The problem with the centralized approaches is that the complexity of the optimization algorithms is usually high and naturally they require the central element in the network. The problem with distributed solutions is that they require a lot of signaling to exchange the CSI between the players. Our motivation for further considerations is thus in taking advantage of both cooperative centralized problem formulation and competitive decentralized behavior of nodes.

Our idea is to let the players compete for resources using some limited but representative information about their CSI, and then to form coalitions and cooperate to refine the resulting spectrum allocation.

In our approach, we assume that there is no central management element but the information exchange between the nodes is also limited.

We postulate the following algorithm which consists of four phases which are: pre-processing phase (PRP), competition phase (ComP), cooperation phase (CooP) and post-processing phase (PPP). This idea is presented on Figure 1.

In the first phase (PRP), each node of the network is preparing the essential data which will be needed in the next competition phase to make efficient allocation of radio resources. This phase it is assumed that the cognitive radio nodes have the information about possible QoS classes in the network, about the available resources and their own CSI (their channel characteristic in the available band). Using this information, the nodes (players) can calculate compact metrics which represent their QoS demands, and their CSI. A good example of such metric representative for the CSI is the effective SNR. The effective SNR may be calculated for the whole bandwidth or for each block (subband) of resources. This metric is not as precise as the channel characteristic but is often considered as a useful representation of the CSI while it is very compact – it is given in one real number. Such compact information can be easily transmitted to each node. Effective SNR was defined, considered and evaluated in [18], [19], [20].

Metrics calculated and exchanged between the players are inputs to the competition phase (ComP). In this phase non-cooperative game models with complete information are considered. We assume that complete information means that all network nodes have exchanged the representative compact information about each other's status (limited to effective SNRs, and their QoS classes) obtained from the previous phase. Thus, a competitive

(non-cooperative) game is played between the players resulting in the number of spectrum units won, i.e. assigned to each player according to her QoS demands and her CSI. As an example of competition we can consider the Cournot competition which was described in [21] and extended by us in [22]. (This game was applied by us for OFDMA systems, and allows assigning the number of subcarriers to each particular user.) Naturally, in case of the frequency selectivity in the whole range of available band the system and players individual throughput and performance depend not only on the number of allocated spectrum units, but also on the particular allocation of these units to each player. Thus this competition phase is completed with only the number of resource units assigned to the players, which will constitute their assets (reflecting their input to the coalition) in the next phase of the algorithm, which is cooperation phase.

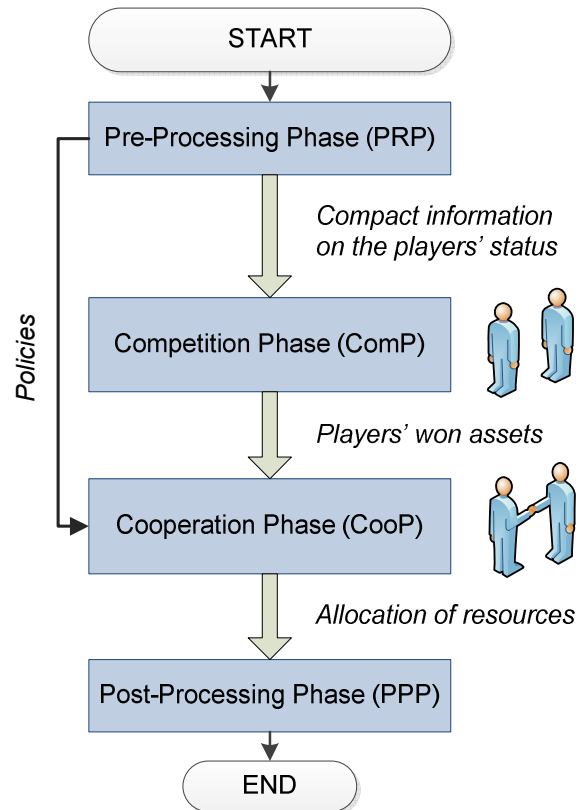


Figure 1. Competition phases for resource allocation

In the cooperation phase (CooP), the result of competition phase is considered. Additionally, some initial regulations and policies concerning spectrum usage have to be made known to the players at this stage. Here, the cooperative game theory, and the coalitional games theory can be used to decide how the process of final resource allocation should look like. In this phase, the players may bargain their assets or form coalitions. Games which may be played here may also aim at power allocation for interference management. As a result of the cooperation phase the concrete allocation of the spectrum units (frequency channels) to the players is done possibly together with the power allocation if the considered system does not use orthogonal channels, i.e. interference between the players and their and power has to be handled.

The result obtained in previous phase is an input to the last phase which is post-processing phase (PPP). In this phase, the transmit power may be allocated if it was not done in cooperation phase. For this purpose the classic water-filling can be applied or the game against the nature. An example of a game against the nature for power allocation was presented in [23]. In this phase also statistics may be calculated, that can be used in the future play of this game.

3.2 Competition for OFDMA

In previous section we described the general competition framework which may be used for spectrum sharing. Here we present an example algorithm of competition between users interested in effective resource utilization of the orthogonal channels in OFDMA. An algorithm is presented on Figure 2.

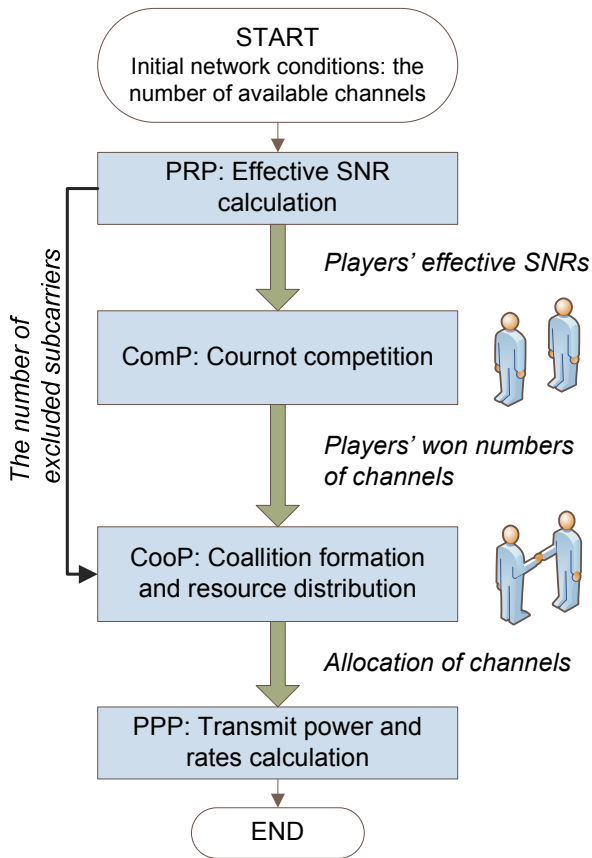


Figure 2. Competition algorithm for spectrum sharing

As an input to the game there are only two parameters necessary, which are: the available bandwidth size and the number of available subcarriers, denoted by K , which will be shared among the nodes (players) competing for them. In the first phase (PRP) each user separately calculates the effective SNR for the whole available bandwidth. This process is carried out in the following way. For the Rayleigh channel with Gaussian noise, each user is doing local water-filling as if it was the only one user in a channel or uses the constant power for each subcarrier. Then the effective SNR $\gamma_{\text{eff},i}$ for each user i is calculated according to the following formula, [20]:

$$\gamma_{\text{eff},i} = -\beta \cdot \ln \left(\frac{1}{K} \cdot \sum_{k=1}^K e^{-\frac{\gamma_{k,i}}{\beta}} \right), \quad (1)$$

where β is an optimization/adjustment parameter which depends on the modulation and coding scheme and $\gamma_{n,i}$ is a SNR on n -th subcarrier of i -th user. The exponential – effective SNR mapping (EESM) method was used.

Each player defines also her QoS class parameters, i.e. the priority of data in her buffers, the revenue parameter (denoted by r_i) and the target error probability (denoted by P_{e_i}). After calculating the effective SNR, all nodes broadcast the triples $(\gamma_{\text{eff},i}, r_i, P_{e_i})$ to the other nodes.

Then, in the competition phase, the simplified Cournot game is played [22]. This is the modified version of the original Cournot Competition which was described in [21]. This game was modified and adjusted to the OFDMA systems and was simplified. In first step of the Cournot Competition every player calculates the spectral efficiency of all the other players. This spectral efficiency for the i -th player (denoted by η_i) is determined by the following formula [24]:

$$\eta_i = \log_2 (1 + \alpha_i \cdot \gamma_{\text{eff},i}), \quad (2)$$

where for QAM modulation schemes

$$\alpha_i = \frac{1.5}{\ln \left(\frac{0.2}{P_{e_i}} \right)}. \quad (3)$$

After calculating the spectral efficiency for each player the profit function (denoted by π_i) is calculated according to the following formula:

$$\pi_i(\mathbf{b}) = r_i \cdot \eta_i \cdot b_i - c(\mathbf{b}), \quad (4)$$

where b_i is the amount of spectrum which will maximize this payoff function, $c(\mathbf{b})$ is the cost function dependent on the vector $\mathbf{b} = (b_1, \dots, b_N)$, and N is the number of players. The cost function is given by:

$$c(\mathbf{b}) = x + y \cdot \left(\sum_j b_j \right)^\tau, \quad (5)$$

where x may reflect the fixed cost of spectrum sharing (expressed in some monetary units), y is the cost of spectrum unit and τ is the factor which impacts the cost of spectrum sharing. For simplicity we consider only $\tau = 1$. The profit π_i is a concave function of b_i and thus the maximum may be found by solving the following equation:

$$\frac{\partial \pi_i}{\partial b_i} = 0. \quad (6)$$

Thus, the best response function for the i -th player can be obtained and it is given by (for $\tau = 1$):

$$b_i^* = \frac{1}{2} \cdot \left(\frac{r_i \cdot \eta_i - x}{y} - \sum_{i \neq j} b_j \right). \quad (7)$$

Furthermore, the Nash Equilibrium (NE) as a solution can be obtained by solving the following set of equations:

$$\mathbf{A} \cdot \mathbf{b}^{*T} = \mathbf{z}, \quad (8)$$

where elements of vector \mathbf{z} are given by:

$$z_i = \frac{r_i \cdot \eta_i - x}{y} \quad (9)$$

and elements of matrix \mathbf{A} (which is the square matrix $N \times N$) are given by:

$$a_{i,j} = \begin{cases} 2 & \text{for } i = j \\ 1 & \text{otherwise} \end{cases}. \quad (10)$$

Finally the vector \mathbf{b}^{*T} which is the NE is obtained easily because the matrix \mathbf{A} is a rank one modification of the unity matrix.

In case if there was only one player (monopoly case) we have the following solution (here we do not have to limit the solution to $\tau = 1$):

$$b_i^* = \tau \sqrt{\frac{r_i \cdot \eta_i - x}{y \cdot (\tau + 1)}} \text{ for } \frac{r_i \cdot \eta_i - x}{y \cdot (\tau + 1)} \geq 0 \quad (11)$$

This value will be referenced later in some variants of the above described Cournot Competition. In the case, when there are some resources still not used there can be an option to reallocate them. In such a case, after calculation of vector \mathbf{b}^{*T} (NE) the sum of the elements of vector \mathbf{b}^{*T} (denoted by D) is calculated:

$$D = \sum_i b_i^* \quad (12)$$

and the final assignment of the number of resource units (denoted by s_i) can be done:

$$s_i = \left\lfloor \frac{K \cdot b_i^*}{D} \right\rfloor \quad (13)$$

Further in this paper we consider the following variants of the Cournot Competition. The first one is a game presented above and will be further called Cournot1 (in Section 4). The second one is a game with minimum demand which is calculated if the value b_i^* is lower than one half of value in the monopoly case defined by formula (11) and is equal to this value. This game will be called Cournot2. The third option is the monopoly case, i.e. all players behave as if they were monopolists, and the values of b_i^* are calculated according to the formula (11). This game will be called Cournot3. The games Cournot1 and Cournot2 are defined with parameter $\tau = 1$, game Cournot3 is for $\tau = 1, 2, 3$ respectively). In the Cournot1 players with high revenue parameter and good effective SNR are strongly prioritized. The games Cournot2 and Cournot3 assure better fairness. The final results of the Cournot competition are the values s_i which are input to the cooperation phase.

In the cooperation phase the coalitions are formed just to define the order of spectrum allocation. The stronger the coalition in

terms of their assets (the total number of assigned subcarriers), the higher priority in the order of acquiring the resources. There may be a number of ways to form coalitions. In this paper we will examine three following options. The first basic option is to not form coalitions, i.e. the coalitions consist of single players. In such a case the players occupy available subcarriers according the number of assigned subcarriers from the player with the highest s_i to the user with the lowest s_i . The second option could be to form random coalitions between random two players. The third and the most promising option is to form coalitions that can obtain the majority of resources, yet having enough flexibility in sharing them between the coalitionists. In such a case, the strongest player (with the highest number of s_i) would form a coalition with the weakest player (the lowest number of s_i) then the second strongest user with the second weakest user etc. Then, again the coalition with the highest number of resources is the first one for spectrum assignment. In the remainder of this paper, we will call this form of coalition formation: *power coalitions*.

In every option of coalition's formation, the players with the higher number of resources are prioritized. The main goal for this phase is to mix the players with the highest number of resources, in average having better CSI than others and higher priority class, with the players having worse CSI and lower priority. This should improve fairness in resource sharing and premium some users with worse CSI. Thus, although the Cournot competition assures more spectrum resources to the players of the higher status (with better CSI) and having the highest priority (which is translated to revenue parameter) the fairness of the allocated resources can be improved at the cooperation stage by letting the weak players to choose their best subcarriers when they are in a coalition with the strong one.

Finally in the post-processing phase the power allocation is done according to the water-filling principle or constant power to each subcarrier. The statistics, useful for the future, are also calculated.

4. SIMULATION MODEL

4.1 System description

In this section below, we present simulation results of the applied cooperation methodology for spectrum sharing (presented in Fig. 2) in the example OFDMA system. The following system and network parameters have been assumed:

- $N = 8$ nodes (players) in the considered network area,
- $K = 192$ subcarriers available for sharing, in 5 MHz of available bandwidth for an LTE-like transmission with 15kHz of one subcarrier channel,
- Rayleigh fading outdoor rural channel with exponentially decaying power profile,
- Assumed total transmit power in the system is limited and fixed, and translates to SNR of 25 dB for each subcarrier at the channel input,
- Average SNR for our first considered scenario was 20 dB for each user at the output of the channel, while for our second considered scenario half of users have poorer channel quality expressed in additional 8 dB SNR loss.
- Adopted parameter $\beta = 30$ for effective SNR calculation,

- The parameters assumed in for the Cournot oligopoly game:
 - $x = 0, y = 1,$
 - $\tau = 1$ for Cournot1 and Cournot2 and $\tau = 1, 2$ and 3 respectively for Cournot3,
 - Target bit error probability is assumed to be 10^{-4} the same for all users,
 - Four priority classes have been assumed for the considered traffic: $r_1 = 0.8$ for player 1 and 2 (P1, P2), $r_2 = 1.6$ for player 3 and 4 (P3, P4), $r_3 = 2.4$ for player 5 and 6 (P5, P6) and $r_4 = 3.2$ for player 7 and 8 (P7, P8), where the higher priority the higher revenue parameter,
- Monte Carlo method was used with 1000 runs for each set of parameters.

4.2 Simulation results

First, we present results for players with similar channels, i.e. average SNR for each player's link is equal to 20 dB. Thus, also the effective SNRs calculated over the whole available band at the beginning of the game would be similar for every player. Note, that still some players are in a better position than others, since their priority classes are diverse. After the application of the cooperation algorithm we can calculate the spectral efficiency for the whole system taking the allocation of the subcarriers to the players into account, as well as their subchannel qualities at these subcarriers (players SNRs at their allocated subcarriers). In Table 1, we present the average obtained spectral efficiency for the assumed target BER for various types of the considered Cournot competition discussed in the previous section and compare it with the Round-Robin and Max SNR methods of spectrum allocation. Although both Round-Robin and Max SNR are centralized they are useful as benchmarks for the comparison of spectral efficiency and fairness. (MaxSNR algorithm results in the highest spectral efficiency, while the Round-Robin results in the best fairness.) Let us note, that the spectral efficiencies obtained with our cooperation methodology are always lower than the values for MaxSNR and higher than respective values obtained for the Round-Robin algorithm. The highest spectral efficiency for the cooperation method is obtained with no coalition formation, simply because the players with the highest effective SNRs are first in turn to acquire resources.

In Table 2 we present the utilization of resources in terms of the average number of assigned subcarriers. One can see that the most of available subcarriers are utilized when Cournot1 game is played at the competition stage (ComP).

In Table 3 we have presented the number of subcarriers allocated to each player after ComP. One can see that depending on the traffic priorities, the players can obtain various number of resources after this phase, i.e. P1 and P2 won the lowest number of subcarriers, while P7 and P8 – the highest.

In Tables 4 – 8 the players' throughput is presented after the cooperation phase for each variant of the Cournot Competition. In these tables, one can observe that the players with higher priority classes have better chance to achieve higher throughput, what results from the won number of subcarriers after the ComP. In the same time when they start to form coalitions, the players with lower priority classes can obtain higher throughput than in

the case when they would not form coalitions. On the contrary, the players with higher priorities obtain slightly lower throughput in a coalition when compared with no coalition formation scheme. But this creates the desired situation of fairness, because if the strong players wouldn't like to form a coalition, the rest of the players would and they would take over the resources, leaving lower choice for that player.

Table 1. Overall players' network spectral efficiency [bit/s/Hz]

| Game type | Round Robin | No. of coalitions | Random coalitions | Power coalitions | Max SNR |
|---------------------------------|-------------|-------------------|-------------------|------------------|---------|
| Cournot 1 ($\tau = 1$) | 4.3036 | 5.1942 | 5.1829 | 5.1825 | 5.7555 |
| Cournot 2 ($\tau = 1$) | 4.2969 | 5.4317 | 5.4262 | 5.4210 | 5.7576 |
| Cournot 3 ($\tau = 1$) | 4.2969 | 5.4609 | 5.4535 | 5.3961 | 5.7558 |
| Cournot 3 ($\tau = 2$) | 4.2916 | 5.4775 | 5.4795 | 5.4567 | 5.7544 |
| Cournot 3 ($\tau = 3$) | 4.2891 | 5.4824 | 5.4868 | 5.4842 | 5.7596 |

Table 2. Allocated resources (no. of subcarriers)

| Game type | Cournot 1 ($\tau = 1$) | Cournot 2 ($\tau = 1$) | Cournot 3 ($\tau = 1$) | Cournot 3 ($\tau = 2$) | Cournot 3 ($\tau = 3$) |
|----------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Resource used | 190.027 | 188.042 | 187.948 | 187.928 | 188.159 |

Table 3. Average number of subcarriers assigned to players P1-P8 after ComP

| Game type | Cournot1 ($\tau = 1$) | Cournot 2 ($\tau = 1$) | Cournot 3 ($\tau = 1$) | Cournot 3 ($\tau = 2$) | Cournot 3 ($\tau = 3$) |
|---------------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Player | | | | | |
| P 1 | 0 | 6.7230 | 9.0850 | 15.0840 | 17.7060 |
| P 2 | 0 | 6.7300 | 9.1040 | 15.0660 | 17.7200 |
| P 3 | 0 | 13.9050 | 18.6820 | 21.6100 | 22.3940 |
| P 4 | 0.0050 | 13.9130 | 18.6890 | 21.6260 | 22.3660 |
| P 5 | 28.7500 | 22.8440 | 28.2560 | 26.5670 | 25.6770 |
| P 6 | 28.7230 | 22.9070 | 28.3310 | 26.5230 | 25.6760 |
| P 7 | 66.0960 | 50.5330 | 37.9770 | 30.7000 | 28.3180 |
| P 8 | 66.4530 | 50.4870 | 37.8240 | 30.7520 | 28.3020 |

Table 4. Players' achieved throughput [Mbit/s] for Cournot1

| Player | Round Robin | No coalition s | Random coalition s | Power coalition s | Max SNR |
|------------|-------------|----------------|--------------------|-------------------|---------|
| P 1 | 1.5195 | 0 | 0 | 0 | 1.9720 |
| P 2 | 1.5107 | 0 | 0 | 0 | 2.0354 |
| P 3 | 1.5071 | 0.0002 | 0.0001 | 0.0002 | 1.8794 |
| P 4 | 1.5096 | 0 | 0 | 0 | 2.0149 |
| P 5 | 1.5234 | 2.0671 | 2.1298 | 2.1512 | 2.0342 |
| P 6 | 1.5310 | 2.0525 | 2.1373 | 2.1424 | 2.0867 |
| P 7 | 1.5256 | 5.3471 | 5.2113 | 5.1856 | 2.1241 |
| P 8 | 1.5194 | 5.3163 | 5.1944 | 5.1418 | 2.0846 |

Table 5. Players' achieved throughput [Mbit/s] for Cournot2

| Player | Round Robin | No coalitions | Random coalitions | Power coalitions | Max SNR |
|--------|-------------|---------------|-------------------|------------------|---------|
| P 1 | 1.4798 | 0.4777 | 0.4861 | 0.5804 | 1.8628 |
| P 2 | 1.4738 | 0.4675 | 0.4864 | 0.5805 | 1.9221 |
| P 3 | 1.4743 | 1.0708 | 1.0538 | 0.9504 | 1.9745 |
| P 4 | 1.4844 | 1.0742 | 1.0590 | 0.9546 | 1.9466 |
| P 5 | 1.4948 | 1.8786 | 1.8321 | 1.7304 | 1.9706 |
| P 6 | 1.4931 | 1.8781 | 1.8178 | 1.7358 | 2.0949 |
| P 7 | 1.4839 | 4.2050 | 4.1737 | 4.1847 | 2.0360 |
| P 8 | 1.4907 | 4.2351 | 4.1953 | 4.2114 | 2.0353 |

Table 6. Players' achieved throughput [Mbit/s] for Cournot3 ($\tau = 1$)

| Player | Round Robin | No coalitions | Random coalitions | Power coalitions | Max SNR |
|--------|-------------|---------------|-------------------|------------------|---------|
| P 1 | 1.4750 | 0.6443 | 0.6674 | 0.7333 | 1.9705 |
| P 2 | 1.4802 | 0.6437 | 0.6590 | 0.7277 | 1.8881 |
| P 3 | 1.4861 | 1.4688 | 1.4672 | 1.4413 | 1.9694 |
| P 4 | 1.4773 | 1.4586 | 1.4527 | 1.4638 | 2.0116 |
| P 5 | 1.4871 | 2.3481 | 2.3100 | 2.2799 | 1.9960 |
| P 6 | 1.4841 | 2.3375 | 2.2974 | 2.2713 | 2.0211 |
| P 7 | 1.4824 | 3.2492 | 3.1713 | 2.9667 | 1.9497 |
| P 8 | 1.4721 | 3.2418 | 3.1753 | 2.9819 | 1.9855 |

Table 7. Players' achieved throughput [Mbit/s] for Cournot3 ($\tau = 2$)

| Player | Round Robin | No coalitions | Random coalitions | Power coalitions | Max SNR |
|--------|-------------|---------------|-------------------|------------------|---------|
| P 1 | 1.4825 | 1.0703 | 1.0903 | 1.0907 | 1.9593 |
| P 2 | 1.4830 | 1.0729 | 1.0962 | 1.0929 | 1.9118 |
| P 3 | 1.4703 | 1.7362 | 1.7248 | 1.8435 | 1.9178 |
| P 4 | 1.4723 | 1.7341 | 1.7431 | 1.8473 | 1.9408 |
| P 5 | 1.4771 | 2.2446 | 2.2015 | 2.2872 | 1.9757 |
| P 6 | 1.4835 | 2.2463 | 2.1951 | 2.2885 | 1.9921 |
| P 7 | 1.4690 | 2.6624 | 2.5919 | 2.2684 | 2.0202 |
| P 8 | 1.4830 | 2.6704 | 2.6137 | 2.3056 | 2.0561 |

Table 8. Players' achieved throughput [Mbit/s] for Cournot3 ($\tau = 3$)

| Player | Round Robin | No coalitions | Random coalitions | Power coalitions | Max SNR |
|--------|-------------|---------------|-------------------|------------------|---------|
| P 1 | 1.4839 | 1.2658 | 1.2942 | 1.2679 | 1.9919 |
| P 2 | 1.4735 | 1.2456 | 1.2831 | 1.2796 | 1.9617 |
| P 3 | 1.4798 | 1.8125 | 1.8050 | 1.9116 | 1.9964 |
| P 4 | 1.4748 | 1.8204 | 1.7966 | 1.9119 | 1.9749 |
| P 5 | 1.4731 | 2.1779 | 2.1290 | 2.2117 | 1.9223 |
| P 6 | 1.4808 | 2.1845 | 2.1397 | 2.2131 | 1.9734 |
| P 7 | 1.4712 | 2.4617 | 2.4079 | 2.1181 | 1.9325 |
| P 8 | 1.4768 | 2.4641 | 2.4127 | 2.1334 | 2.0788 |

In Tables from 9 – 15 we present the analogous results to the ones from Tables 1 – 8 for players with noticeable channel quality differentiation. In this considered case, one user from each traffic class has her average SNR at the channel output in the total available band (players P1, P3, P5, P7) lower than the rest of the players by 8 dB. Thus, the players are now differentiated due to diverse revenue parameters and average SNRs.

Table 9. Overall players' network spectral efficiency [bit/s/Hz]

| Game type | Round Robin | No coalitions | Random coalitions | Power coalitions | Max SNR |
|--------------------------|-------------|---------------|-------------------|------------------|---------|
| Cournot1 ($\tau = 1$) | 3.5244 | 4.9792 | 4.9712 | 4.9736 | 5.6605 |
| Cournot 2 ($\tau = 1$) | 3.5131 | 5.1732 | 5.1722 | 5.1725 | 5.6569 |
| Cournot 3 ($\tau = 1$) | 3.5184 | 5.1922 | 5.1964 | 5.2066 | 5.6597 |
| Cournot 3 ($\tau = 2$) | 3.5159 | 5.2019 | 5.2112 | 5.2476 | 5.6584 |
| Cournot 3 ($\tau = 3$) | 3.5159 | 5.2024 | 5.2176 | 5.2540 | 5.6526 |

Table 10. Allocated resources (no. of subcarriers)

| Game type | Cournot 1 ($\tau = 1$) | Cournot 2 ($\tau = 1$) | Cournot 3 ($\tau = 1$) | Cournot 3 ($\tau = 2$) | Cournot 3 ($\tau = 3$) |
|-----------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Resource s used | 189.7470 | 188.0330 | 187.9740 | 188.0240 | 187.9970 |

Table 11. Average number of subcarriers after the Cournot Competitions

| Game type | Cournot 1 ($\tau = 1$) | Cournot 2 ($\tau = 1$) | Cournot 3 ($\tau = 1$) | Cournot 3 ($\tau = 2$) | Cournot 3 ($\tau = 3$) |
|-----------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Player | | | | | |
| P 1 | 0 | 5.2250 | 7.6160 | 13.8490 | 16.6250 |
| P 2 | 0 | 7.4180 | 10.6730 | 16.4350 | 18.6950 |
| P 3 | 0.0920 | 10.8720 | 15.5190 | 19.7340 | 21.0580 |
| P 4 | 4.4510 | 15.2410 | 21.8780 | 23.4410 | 23.6910 |
| P 5 | 13.2090 | 17.3480 | 23.5230 | 24.2270 | 24.1870 |
| P 6 | 44.9600 | 34.0830 | 33.0260 | 28.8280 | 27.1680 |
| P 7 | 40.6530 | 32.2390 | 31.5380 | 28.0950 | 26.6160 |
| P 8 | 86.3820 | 65.6070 | 44.2010 | 33.4150 | 29.9570 |

Table 12. Players' achieved throughput [Mbit/s] for Cournot1

| Player | Round Robin | No coalitions | Random coalitions | Power coalitions | Max SNR |
|--------|-------------|---------------|-------------------|------------------|---------|
| P 1 | 0.9492 | 0 | 0 | 0 | 1.1435 |
| P 2 | 1.4837 | 0 | 0 | 0 | 2.6165 |
| P 3 | 0.9436 | 0.0063 | 0.0073 | 0.0075 | 1.1578 |
| P 4 | 1.5035 | 0.3247 | 0.3287 | 0.3596 | 2.7322 |
| P 5 | 0.9573 | 0.7414 | 0.7997 | 0.8082 | 1.1650 |
| P 6 | 1.5035 | 3.3980 | 3.3838 | 3.3660 | 2.9019 |
| P 7 | 0.9796 | 2.5591 | 2.5375 | 2.5684 | 1.1822 |
| P 8 | 1.4952 | 6.9606 | 6.8328 | 6.6822 | 2.8028 |

Table 13. Players' achieved throughput [Mbit/s] for Cournot2

| Player | Round Robin | No coalition s | Random coalition s | Power coalition s | Max SNR |
|--------|-------------|----------------|--------------------|-------------------|---------|
| P 1 | 0.9377 | 0.2576 | 0.3063 | 0.4403 | 1.1158 |
| P 2 | 1.4640 | 0.5383 | 0.5372 | 0.6044 | 2.5535 |
| P 3 | 0.9394 | 0.6519 | 0.6700 | 0.6655 | 1.1776 |
| P 4 | 1.4569 | 1.2010 | 1.1524 | 0.9987 | 2.6203 |
| P 5 | 0.9535 | 1.1781 | 1.1436 | 0.9970 | 1.2354 |
| P 6 | 1.4795 | 2.8089 | 2.7596 | 2.7440 | 2.7403 |
| P 7 | 0.9534 | 2.3393 | 2.2734 | 2.2357 | 1.2017 |
| P 8 | 1.4825 | 5.4656 | 5.4441 | 5.4613 | 2.8310 |

Table 14. Players' achieved throughput [Mbit/s] for Cournot3 ($\tau = 1$)

| Player | Round Robin | No coalition s | Random coalition s | Power coalition s | Max SNR |
|--------|-------------|----------------|--------------------|-------------------|---------|
| P 1 | 0.9399 | 0.3753 | 0.4519 | 0.6367 | 1.1416 |
| P 2 | 1.4647 | 0.7815 | 0.7825 | 0.8050 | 2.5755 |
| P 3 | 0.9401 | 0.9649 | 0.9968 | 1.0033 | 1.1303 |
| P 4 | 1.4598 | 1.7636 | 1.7178 | 1.6652 | 2.7057 |
| P 5 | 0.9443 | 1.6427 | 1.6298 | 1.5320 | 1.1846 |
| P 6 | 1.4576 | 2.7901 | 2.7150 | 2.5622 | 2.7577 |
| P 7 | 0.9433 | 2.3695 | 2.2893 | 2.1810 | 1.1922 |
| P 8 | 1.4612 | 3.7914 | 3.7247 | 3.7448 | 2.6704 |

Table 15. Players' achieved throughput [Mbit/s] for Cournot3 ($\tau = 2$)

| Player | Round Robin | No coalition s | Random coalition s | Power coalition s | Max SNR |
|--------|-------------|----------------|--------------------|-------------------|---------|
| P 1 | 0.9488 | 0.6639 | 0.7816 | 1.0317 | 1.1783 |
| P 2 | 1.4555 | 1.2446 | 1.2298 | 1.1811 | 2.6198 |
| P 3 | 0.9379 | 1.2914 | 1.3029 | 1.3529 | 1.1485 |
| P 4 | 1.4485 | 1.9305 | 1.8834 | 1.8813 | 2.6608 |
| P 5 | 0.9435 | 1.7780 | 1.7454 | 1.7633 | 1.2016 |
| P 6 | 1.4546 | 2.4735 | 2.4078 | 2.2426 | 2.6828 |
| P 7 | 0.9350 | 2.1709 | 2.0974 | 2.0360 | 1.1649 |
| P 8 | 1.4603 | 2.9084 | 2.8578 | 2.7117 | 2.6630 |

In case this case, resources are allocated to users due to their effective SNR and the priorities of their data traffic.

Let us note that the Cournot1 game strongly promotes users with high priority (see Table 3) and higher SNR (see Table 11). The Cournot2 game assures more fair resources allocation than Cournot1. The Cournot3 game assures the fairest resources allocation so it can be translated that the impact of the SNR and priority is reduced but it is still has a role in this game. This considered Cournot competition treats all players differentially according to their priorities and SNRs.

The cooperation phase of the algorithm assures the final resource allocation to each user. Coalitions' forming assures that users are mixed and in some cases users which were assigned less resources

are in better position than users which were assigned more resources in terms of the flexibility of choosing their best subcarriers. This is important especially in case when players are differentiated not only due to their priorities but also their SNRs.

Table 16. Players' achieved throughput [Mbit/s] for Cournot3 ($\tau = 3$)

| Player | Round Robin | No coalition s | Random coalition s | Power coalition s | Max SNR |
|--------|-------------|----------------|--------------------|-------------------|---------|
| P 1 | 0.9415 | 0.7743 | 0.9053 | 1.1313 | 1.1949 |
| P 2 | 1.4497 | 1.4351 | 1.4060 | 1.3577 | 2.7045 |
| P 3 | 0.9403 | 1.4048 | 1.4259 | 1.4646 | 1.1675 |
| P 4 | 1.4515 | 1.9650 | 1.9154 | 1.9420 | 2.6019 |
| P 5 | 0.9373 | 1.8004 | 1.7835 | 1.8011 | 1.2021 |
| P 6 | 1.4483 | 2.3410 | 2.2809 | 2.1164 | 2.6341 |
| P 7 | 0.9339 | 2.0846 | 1.9985 | 1.9805 | 1.1656 |
| P 8 | 1.4541 | 2.6183 | 2.5677 | 2.3587 | 2.5754 |

5. CONCLUSIONS

We have presented the practical methodology called co-competition for spectrum sharing in the decentralized network, where the competition between the potential spectrum users can be observed. We allow the competitors to first play the non-cooperative complete-information game for resources based on the compact representative information on their channel qualities. Then one can observe that the players have an incentive to improve their transmission performance by forming coalitions among themselves, and thus, they start to cooperate locally. The presented methodology results in relatively high spectral efficiency and in some degree of fairness in resource distribution. In the same time, the amount of control traffic necessary to exchange some basic information is also limited, what shows that our methodology provides a good trade-off between centralized and distributed but ineffective solutions.

6. ACKNOWLEDGMENTS

The research leading to these results has received funding from the Polish Ministry of Science and Higher Education, under the grant No. 779/N-COST2010/0 which supports participation in the European COST Action IC0902.

7. REFERENCES

- [1] A. M. Brandenburger, B. J. Nalebuff 'Co-opetition: A Revolutionary Mindset That Combines Competition and Co-operation: The Game Theory Strategy That's Changing the Game of Business', Doubleday Publication Pre, 1996
- [2] <http://en.wikipedia.org/wiki/Coopetition>
- [3] Zhang Rui; Zhang Jin-long; , "Research on co-opetition of mobile TV based on network convergence the case of CMMB," *Information Management and Engineering (ICIME), 2010 The 2nd IEEE International Conference on*, vol., no., pp.490-494, 16-18 April 2010

- [4] Heng Liu; , "Co-Opetition and Knowledge Sharing in Supply Chain," *Information Science and Engineering (ICISE), 2009 1st International Conference on* , vol., no., pp.4237-4240, 26-28 Dec. 2009
- [5] T. Teredesai, V.C. Ramesh, "A Multi-Agent Mixed Initiative System for Real-time Scheduling", IEEE International Conference on Systems, Man and Cybernetics, 11-14 Oct 1998, pp. 439 - 444
- [6] Zhong Huiling; An Lili; Huang Xiaoyu; Cai Wenxue; , "The game playing of port co-opetition Between Hong Kong and Shenzhen based on AHP," *Logistics Systems and Intelligent Management, 2010 International Conference on* , vol.3, no., pp.1522-1526, 9-10 Jan. 2010
- [7] Xin Zhou; Li-Kun Wang; , "Static Game Analysis on Different Strategies Adopted by Ports," *Wireless Communications, Networking and Mobile Computing, 2008. WiCOM '08. 4th International Conference on* , vol., no., pp.1-4, 12-14 Oct. 2008
- [8] Zhang Peilin; Yang Long; Wang Hui; , "Game analysis of price competition between Hong Kong and Shenzhen container port based on bertrand model," *Environmental Science and Information Application Technology (ESIAT), 2010 International Conference on* , vol.2, no., pp.731-734, 17-18 July 2010
- [9] Xin Zhou; Jianhua Ji; , "Study on evolutionary stable strategy of ports," *Service Operations and Logistics, and Informatics, 2008. IEEE/SOLI 2008. IEEE International Conference on* , vol.2, no., pp.2249-2253, 12-15 Oct. 2008
- [10] M. Bengtsson, S. Kock, 'Coopetition in business networks - to cooperate and compete simultaneously', *Industrial Marketing Management*, vol. 29, pp. 411-426, 2000.
- [11] J. Reaidy, D. Diep, P. Massotte, "Management and control of complex production systems: co-opetition through game theory principles and agents based information systems", *Proceedings. IEEE International Conference on Industrial Informatics, INDIN 2003*.
- [12] E. G.Carayannis, J.Alexander 'Virtual, wireless manna: a co-opetitive analysis of the broadband satellite industry', *Technovation*, vol. 21 pp.759-766, 2001
- [13] Y. Luo: 'A coopetition perspective of global competition', *Journal of World Business* vol. 42, pp. 129-144, 2007.
- [14] Z. Guan; D. Yuan; H. Zhang; , "Novel coopetition paradigm based on bargaining theory or collaborative multimedia resource management," *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on* , vol., no., pp.1-5, 15-18 Sept. 2008
- [15] Yi Su; van der Schaar, M.; , "From competition to coopetition: Stackelberg equilibrium in multi-user power control games," *Game Theory for Networks, 2009. GameNets '09. International Conference on* , vol., no., pp.107-116, 13-15 May 2009
- [16] T. Bonald, "A Score-Based Opportunistic Scheduler for Fading Radio Channels", *Proceedings of European Wireless*, pp. 283-292, Feb. 2004.
- [17] C.Y. Wong, R.S. Cheng, K.B. Letaief, R.D. Murch, "Multiuser OFDM with Adaptive Subcarrier, Bit, and Power Allocation" *IEEE Journ. Select. Areas Commun. Vol. 17, No. 10, Oct.1999*, pp. 1747-1758
- [18] Nortel, "Effective SIR computation for OFDM system-level simulations", *TSG-RAN WG1, no. 35, R03-1370*, Nov. 2003
- [19] I. Dages, A. Zalonis, N. Dimitriou, K. Nikitopoulos, A. Polydoros, "Flexible Radio: A Framework for Optimized Multimodal Operation via Dynamic Signal Design", *EURASIP Journal on Wireless Communications and Networking*, No. 2005:3, pp. 284-297
- [20] A. Kliks, A. Zalonis, I. Dages, A. Polydoros, H. Bogucka "PHY Abstraction Methods for OFDM and NOFD Systems ", *Journal of Telecommunications and Information Technology (JTIT) 3/2009*
- [21] D. Niyato, E. Hossain, "Microeconomic models for dynamic spectrum management in cognitive radio networks," chapter in *Cognitive Wireless Communication Networks*, (Eds. V.K. Bhargava and E. Hossain), Springer-Verlag, November 2007.
- [22] M. Parzy, H. Bogucka, "QoS Support in Radio Resource Sharing with the Cournot Competition", *Proc. Int. Workshop on Cognitive Information Processing CIP'10*, Elba, Italy, 14-16 June, 2010
- [23] Bogucka, H.; , "Game Theoretic Model for the OFDM Water-Filling Algorithm with Imperfect Channel State Information," *Communications, 2008. ICC '08. IEEE International Conference on* , vol., no., pp.3814-3818, 19-23 May 2008
- [24] A.J. Goldsmith and S.-G Chua, "Variable rate variable power MQAM for fading channels" *IEEE Trans. Commun.*, vol.45, no.10, pp. 1218-1230, Oct. 1997