Bargaining over the interference channel with total power constraints

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Abstract—In this paper we study the computation of the Nash bargaining solution for the two players, K frequency bands case, under joint FDM/TDM spectrum allocations and total power constraint. The results improve previous analysis by Han et al. We provide a computationally efficient algorithm as well as detailed analysis of the Karush-Kuhn-Tucker (KKT) equations necessary for proving the correctness of the algorithm. Simulation results demonstrating the gain of the NBS over competitive approaches are also provided.

Keywords: Spectrum optimization, distributed coordination, game theory, interference channel, multiple access channel, power constraint.

I. INTRODUCTION

The interference channel is a conflict situation between the interfering links [1]. Each link is considered a player in a general interference game. As such it has been shown that non-cooperative solutions such as the iterative water-filling, which leads to good solutions for the multiple access channel (MAC) and the broadcast channel [2] can be highly suboptimal in interference channel scenarios [3], [4]. To solve this problem there are several possible approaches. Our approach is based on general bargaining theory originally developed by Nash [5]. In his seminal papers, Nash proposed four axioms that any solution to the bargaining problem should satisfy. He then proved that there exists a unique solution satisfying these axioms.

Recently, bargaining theory has gained popularity as a mean for spectrum and resource sharing in interference limited wireless networks. Han et al. [6] analyzed OFDMA systems under total power constraint. In previous papers [7], [8] we provided a computationally efficient solution for the Nash bargaining over the frequency selective channel with power mask constraint using TDM/FDM strategies similar to those used by [6]. Bargaining for the MISO channel (multiple access channel) were considered in [9]. Nockelby et al. [10] consider the important general case of interference channel with general PSD allocation. In this case the problem is non-convex, and a numerical solution is proposed. Schubert and Boche [11], [12] consider the case of log-convex utility function.

As discussed in [8] not every rate vector achievable for the interference channel is relevant. Only rate vectors that dominate component-wise the rates that each user can achieve, independently of the other users coding strategy are of interest. The best rate pairs that can be achieved independently of the other users strategies form a Nash equilibrium [5], and we use these rates as the disagreement point for our Nash bargaining solution. For total power limit the Nash equilibrium is achieved as the fixed point of the Gaussian interference game [13], [4],

[14], [15]. Extensions of the Nash bargaining proposed by Kalai and Somorodinsky [16] are considered in [17], [18].

In this paper we study the existence of Nash Bargaining solution under total power constraint. We limit our analysis to the two user case and show an efficient algorithm for computing the bargaining solution. The problem has been previously studied by the paper of Han et al. [6]. However, in that paper the solution of the KKT equations has been obtained under approximation of high SNR. In this paper we propose an alternative formulation of the problem by different representation of the Lagrangian, using the water levels for each user instead of the power vectors. By adding constraints on the relation between the TDM strategies and the water level, we can show that for each set of water levels there is a single time/frequency allocation that can potentially solve the KKT equations. This results in two-dimensional search over the water levels, with direct computation of the TDM division for any given pair of water levels. We are able to show that there is always an optimal solution where users share at most a single frequency.

II. MODEL FORMULATION

In this section we define the joint FDM/TDM game under total power constraint. This game is different than the game defined in [8] in that the power is not fixed at each band, but the users can optimize their PSD under total power constraint. This implies that the problem is no longer convex.

Definition 2.1: The N player FDM/TDM game $G_{TF}(N, K, P_1, ..., P_N)$ is a game between N players transmitting over K frequency bins under total power constraints for each player. Each user has full knowledge of the channel matrices $\mathbf{H}_k$. The following conditions hold:

1) Strategies for player i are vectors $\boldsymbol{\alpha}_i = [\alpha_{i1}, ..., \alpha_{iK}]^T$ where α_k is the proportion of time the player uses the k'th frequency channel. and power vectors $\mathbf{p}_i = \langle p_i(k) : k = 1, ..., K \rangle$ satisfying its power constraint $\sum_{k=1}^{K} \alpha_i(k)p_i(k) \leq P_i$. The vector $\boldsymbol{\alpha}_i$ is the TDM part of the strategy.

2) The utility of the i'th player is given by

$$\begin{aligned} R_i &= \sum_{k=1}^{K} \alpha_i(k)R_i(k) \\ &= \sum_{k=1}^{K} \alpha_{ik} \log_2 \left(1 + \frac{|h_{ii}(k)|^2 p_i(k)}{\sigma_i^2(k)}\right). \end{aligned} \quad (1)$$

Note that interference is avoided by time sharing at each frequency band, i.e only one player transmits at a given frequency bin at any time.

Since at each time instance each frequency is used by a single user, each user can perform water-filling over its bands, taking

into account the length of the time slots. Also note that if $p_i(k) = 0$ then necessarily $\alpha_i(k) = 0$ for any pareto optimal solution. Similarly, if $\alpha_i(k) = 0$ we have $p_i(k) = 0$. Since each user performs water-filling over its band we can replace its strategy by a choice of the relevant water level L_i and the TDM partition vector $\boldsymbol{\alpha}_i$. Thus,

$$p_i(k) = \left[L_i - \sigma_i^2(k)\right]_+, i = 1, 2. \tag{2}$$

Therefore, the rates can be written as:

$$R_i(k) = \log\left(1 + \frac{\left[L_i - \sigma_i^2(k)\right]_+}{\sigma_i^2(k)}\right). \tag{3}$$

More explicitly the rates are:

$$R_i(k) = \begin{cases} \log\left(\frac{L_i}{\sigma_i^2(k)}\right) & L_i \geq \sigma_i^2 \\ 0 & L_i < \sigma_i^2 \end{cases}. \tag{4}$$

The level L_i is set such that

$$P_i = \sum_{k \in \text{supp}(\boldsymbol{\alpha}_i)} \alpha_i(k)\left[L_i - \sigma_i^2(k)\right]_+. \tag{5}$$

By the comments above if $L_i \leq \sigma_i^2(k)$ we must have $p_i(k) = 0$ so that $\alpha_i(k) = 0$, and therefore $\alpha_i(k)\left[L_i - \sigma_i^2(k)\right] = 0$. Hence, we can write

$$P_i = \sum_{k=1}^{K} \alpha_i(k)\left[L_i - \sigma_i^2(k)\right]. \tag{6}$$

This will significantly simplify the analysis of the KKT equations in the next section. Also by Pareto optimality, we do not allocate bands that are not used to a user, so that the following constraint must be satisfied:

$$\alpha_i(k)\left(L_i - \sigma_i^2(k)\right) \geq 0, \qquad k = 1, ..., K. \tag{7}$$

Similarly to [8] we have from Pareto optimality that for all k:

$$\sum_{i=1}^{N} \alpha_i(k) = 1, \tag{8}$$

except when both users prefer not to use the frequency k. In that case $\alpha_1(k) = \alpha_2(k) = 0$. In any case

$$\sum_{i=1}^{N} \alpha_i(k) \leq 1. \tag{9}$$

Finally, we require that there is at least one point that is as good as the competitive solution, i.e., for all i:

$$R_{iC} \leq \sum_{k=1}^{K} \alpha_i(k)R_i(k). \tag{10}$$

III. ANALYSIS OF KKT

To obtain an efficient algorithm for the power limited two users and K frequency bands case, we explore the KKT conditions for the problem. Since solving the KKT equations is a necessary condition for solving the optimization problem we will show that given water levels L_1, L_2 the problem can be efficiently solved. In the generic case the solution will be unique for each L_1, L_2 and the power constraints will allow us to choose the proper L_1, L_2. However, in certain cases (of probability 0) the channel might satisfy certain non-linear constraints. In this case the problem will be reduced to a convex optimization for solving for $\boldsymbol{\alpha}$ that solves the KKT equations and maximizes the Nash function given L_1, L_2. It is possible to prove that even in these cases, there is an optimal partition of the frequencies where at most a single frequency is shared.

The Lagrangian of the problem $f(\boldsymbol{\alpha})$ is given by

$$\begin{aligned} f(\boldsymbol{\alpha}, L) = & - \sum_{i=1}^{N} \log\left(R_i(\boldsymbol{\alpha}_i) - R_{iC}\right) \\ & + \sum_{k=1}^{K} \lambda_k \left(\sum_{i=1}^{N} \alpha_i(k) - 1\right) \\ & - \sum_{k=1}^{K} \sum_{i=1}^{N} \mu_i(k)\alpha_i(k) \\ & - \sum_{i=1}^{N} \delta_i \left(\sum_{k=1}^{K} \alpha_i(k)R_i(k) - R_{iC}\right) \\ & + \zeta_i \left(\sum_{k=1}^{K} \alpha_i(k)\{L_i - \sigma_i^2(k)\} - P_i\right) \\ & - \sum_{i=1}^{N} \sum_{k=1}^{K} \gamma_{i,k}\alpha_i(k)\left(L_i - \sigma_i^2(k)\right) \end{aligned} \tag{11}$$

Taking the derivative with respect to the variables $\alpha_i(k)$ and L_i and comparing the result to zero, we get

$$\begin{aligned} \frac{df(\boldsymbol{\alpha}, L)}{d\alpha_i(k)} = & - \frac{R_i(k)}{R_i(\boldsymbol{\alpha}_i) - R_{iC}} + \lambda_k - \mu_i(k) - \delta_i \\ & + \zeta_i\left(L_i - \sigma_i^2(k)\right) \\ & - \gamma_{i,k}\left(L_i - \sigma_i^2(k)\right) \end{aligned} \tag{12}$$

$$\begin{aligned} \frac{df(\boldsymbol{\alpha}, L)}{dL_i} = & - \frac{\sum_{k=1}^{K} \alpha_i(k)}{L_i(R_i(\boldsymbol{\alpha}_i) - R_{iC})} \\ & - \delta_i \frac{\sum_{k=1}^{K} \alpha_i(k)}{L_i} \\ & + \zeta_i \sum_{k=1}^{K} \alpha_i(k) \\ & - \sum_{k=1}^{K} \gamma_{i,k}\alpha_i(k) \end{aligned}, \tag{13}$$

with the constraints

$$\begin{aligned} \sum_{i=1}^{N} \alpha_i(k) \leq 1, \\ \sum_{k=1}^{K} \alpha_i(k)\left(L_i - \sigma_i^2(k)\right) = P_i \end{aligned}, \tag{14}$$

and

$$\begin{aligned} \delta_i\left(R_i(\boldsymbol{\alpha}_i) - R_{iC}\right) = 0, \\ \mu_i(k)\alpha_i(k) = 0, \\ \gamma_{i,k}\alpha_i(k)\left(L_i - \sigma_i^2(k)\right) = 0, \\ \gamma_{i,k} \geq 0, \\ \mu_i(k) \geq 0, \delta_i \geq 0. \end{aligned} \tag{15}$$

If there is a solution to the optimization problem, then $\delta_i = 0$ for $i = 1, 2$. Based on (13) we obtain

$$\frac{1}{L_i(R_i(\boldsymbol{\alpha}_i) - R_{iC})} = \zeta_i - \frac{\sum_{k=1}^{K} \gamma_{i,k}\alpha_i(k)}{\sum_{k=1}^{K} \alpha_i(k)} \tag{16}$$

and when $\alpha_i(k) \neq 0$ and $L_i \neq \sigma_i^2(k)$ we get based on (12,14,15,16)

$$\frac{R_i(k) - \frac{\left(L_i - \sigma_i^2(k)\right)}{L_i}}{R_i(\boldsymbol{\alpha}_i) - R_{iC}} = \lambda_k, \qquad (17)$$

or equivalently

$$\frac{R_i(k) - 1 + e^{-R_i(k)}}{R_i(\boldsymbol{\alpha}_i) - R_{iC}} = \lambda_k. \qquad (18)$$

Using equation (18) for $i = 1, 2$ we obtain that

$$\frac{g(R_1(k))}{R_1(\boldsymbol{\alpha}_1) - R_{1C}} = \frac{g(R_2(k))}{R_2(\boldsymbol{\alpha}_2) - R_{2C}}, \qquad (19)$$

where $g(x) = x + e^{-x} - 1$. Therefore

$$\frac{g(R_1(k))}{g(R_2(k))} = \frac{R_1(\boldsymbol{\alpha}_1) - R_{1C}}{R_2(\boldsymbol{\alpha}_2) - R_{2C}}. \qquad (20)$$

Note that the right hand side of (20) is independent of frequency. Hence for all frequencies k, m satisfying $0 < \alpha_1(k), \alpha_1(m) < 1$ we must have

$$\frac{g(R_1(k))}{g(R_2(k))} = \frac{g(R_1(m))}{g(R_2(m))}. \qquad (21)$$

Note also that when $\alpha_i(k) = 0$ we have

$$\frac{R_i(k) - 1 + e^{-R_i(k)}}{R_i(\boldsymbol{\alpha}_i) - R_{iC}} \leq \lambda_k. \qquad (22)$$

since $\mu_i(k) \geq 0$. Furthermore, when $\alpha_1(k) = 0$ we necessarily have

$$\frac{g(R_1(k))}{R_1(\boldsymbol{\alpha}_1) - R_{1C}} \leq \frac{g(R_2(k))}{R_2(\boldsymbol{\alpha}_2) - R_{2C}} \qquad (23)$$

and when $\alpha_2(k) = 0$

$$\frac{g(R_1(k))}{R_1(\boldsymbol{\alpha}_1) - R_{1C}} \geq \frac{g(R_2(k))}{R_2(\boldsymbol{\alpha}_2) - R_{2C}}. \qquad (24)$$

The last two observations will assist us in devising the algorithm later, since we will be able to sort the frequencies according to $g(R_1(k))/g(R_2(k))$.

Given L_1, L_2 we can immediately distinguish the frequencies which are not used by any of the users as those which satisfy $L_1 < \sigma_1^2(k), L_2 < \sigma_2^2(k)$, where $\alpha_1(k) = \alpha_2(k) = 0$ and ignore them. To simplify notation we will assume that we do not have such frequencies, and $\alpha_2(k) = 1 - \alpha_1(k)$. Substituting (1) into (20) we obtain a set of $d = |D|$ (where D is the set of frequencies that satisfy Eq. (25) linear equations in the variables $\alpha_1(1), ..., \alpha_1(K)$:

$$\frac{g(R_1(k))}{g(R_2(k))} = \frac{\sum_{m=1}^{K} \alpha_1(m) R_1(m)}{\sum_{m=1}^{K} (1 - \alpha_1(m)) R_2(m)}, \quad k \in D, \qquad (25)$$

and a set of $k - d$ inequalities:

$$\begin{array}{ll} \frac{g(R_1(k))}{g(R_2(k))} > \frac{\sum_{m=1}^{K} \alpha_1(m) R_1(m)}{\sum_{m=1}^{K} (1 - \alpha_1(m)) R_2(m)}, & \alpha_1(k) = 1 \\ \frac{g(R_1(k))}{g(R_2(k))} < \frac{\sum_{m=1}^{K} \alpha_1(m) R_1(m)}{\sum_{m=1}^{K} (1 - \alpha_1(m)) R_2(m)}, & \alpha_1(k) = 0 \end{array}. \qquad (26)$$

TABLE I
ALGORITHM FOR COMPUTING THE 2X2 FREQUENCY SELECTIVE NBS
UNDER AVERAGE POWER CONSTRAINT

Initialization:
Compute lower and upper bounds of the water levels, $n = 1, 2$:
$L_{n,min}$- results from water filling with no interference,
$L_{n,max} = P_n + max_k \left(\frac{\sigma_n^2(k)}{h_{nn}(k)} \right)$ - maximum water levels.
Set:
$\triangle P$ - power accuracy.
$\triangle L = \triangle P / K$ - water level accuracy.
Divide the set of possible values of water levels L_1, L_2
to a grid with M^2 points with granulite $\triangle L$.
Computation: For any point in the $2 - D$ grid :
Compute the rates $R_n(k), n = 1, 2$.
Sort the frequency bin according to the ratio
$\frac{g(R_1(k))}{g(R_2(k))}$ in decreasing order.
Solve NBS according to Eq. (23).
Compute the total power used by each user.
Compute the rates obtained by NBS.
Select the point in the grid that maximizes Nash Bargaining function,
and has total power per user in the range $[P_n - \triangle P, P_n + \triangle P]$

Let $\mathbf{r}_i = \left(R_i(k_1), ..., R_i(k_{|D|})\right)^T$, $k_1, .., K_{|D|} \in D$, and $\mathbf{g}_i = \left(g(R_i(k_1)), ..., g(R_i(k_{|D|}))\right)$. The equations above can be written as

$$\left(\mathbf{g}_1 \mathbf{r}_2^T + \mathbf{g}_2 \mathbf{r}_1^T\right) \boldsymbol{\beta} = (\mathbf{r}_2^T \mathbf{1}) \mathbf{g}_1, \qquad (27)$$

where $\boldsymbol{\beta} = [\boldsymbol{\alpha}_{k_1}, ..., \boldsymbol{\alpha}_{k_d}]^T$.

Equations (27), (5), and inequalities provide a unique solution as long as there are at most two frequencies which satisfy (20). This already provides a simple algorithm for solving the 2 users case. Perform a two-dimensional search over L_1, L_2 and for each L_1, L_2 find the cutoff frequencies which satisfy (20). This defines a unique partition if there are at most two such frequencies. Otherwise for these L_1, L_2 we can solve a convex optimization problem, for maximizing

$$f(\boldsymbol{\alpha}, L) = -\sum_{i=1}^{N} \log\left(R_i(\boldsymbol{\alpha}_i) - R_{iC}\right) \qquad (28)$$

under the linear constraints (27), (5). It turns out (the proof is omitted due to its complexity) that an optimal solution can always be chosen such that at most a single frequency is shared between the users. Unlike the power mask constraint case, this proof is significantly more complicated. Full description of the algorithm will be provided in the final version of this paper.

IV. SIMULATIONS

In this section we compare in simulations the Nash Bargaining Solution to the competitive solution for frequency selective fading under average power constraint. We performed extensive simulations that demonstrate the advantage of the NBS over the competitive approach for the frequency selective fading channel, as a function of the mean interference power. The performance of the NBS was evaluated according to two criteria. First, the minimum relative improvement, $\Delta_{\min}$, describing the individual minimum price of anarchy, that a player can gain by cooperation. Second, the maximum relative

improvement, $\Delta_{\max}$, describing the individual maximum gain by cooperation. These criteria are defined as follows:

$$\Delta_{\min} = \min\left\{R_1^{NBS}/R_1^C, R_2^{NBS}/R_2^C\right\}$$
$$\Delta_{\max} = \max\left\{R_1^{NBS}/R_1^C, R_2^{NBS}/R_2^C\right\} \quad (29)$$

In this simulation we demonstrate the advantage of the Nash bargaining solution over competitive approach of iterative water filling (IWF), for a frequency selective interference channel. We assumed that two players having direct channels that are standard Rayleigh fading channels ($\sigma^2 = 1$), with SNR=30 dB, and co-channel interference due to the second player (h_{ij}). The SINR of each player was varied from 8 dB to 1 dB ($\sigma_{h_{ij}}^2 = 0.1, ; 1$). We have used 16 frequency bins. At each pair of variances $\sigma_1^2 = \sigma_{h_{21}}^2, \sigma_2^2 = \sigma_{h_{12}}^2$, we randomly picked 1000 channels (each comprising of 16 2x2 matrices). The results of the minimal relative gain, and the maximum relative gain (29), are depicted in figures (1), and (2), respectively. We can clearly see that the relative gain of the Nash bargaining solution over the competitive solution highly depends on the SINR. The maximum value of the gain, which is about 1.8 (80%) is obtained when weaker player has SINR of 1 db (his NBS gain is 1.8), and the strongest player has SINR of 8 dB (his NBS gain is 1.1). If we are measuring the minimum NBS, we see that both of the players can gain due to cooperation between 10%-40%, when the SINR is limited to the range of 1 dB-8 dB. The gain reduces dramatically if the SINR is very high or very low. At very high SINR, the result of IWF is partitioning of the band between the two users, so there is no NBS since the strongest player will not agree to get less than R_{ic}. At very low SINR, the effect of the interference is very small and the two players prefer to share the all band. The results that we show are in contrast to NBS under power mask constraint, where the gain increases as SINR decreases. This is not surprising, since under power mask constraint the players can not use water filling for optimized power allocation.

V. CONCLUSIONS

In this paper we extended the results of [7], [8] to the two players frequency selective channel with total power constraint. Similarly to the previous case we have a very efficient algorithm. However, in contrast to the PSD limited case, the algorithm requires initial step of iterative waterfilling and a two dimensional optimization over the water levels in the Nash bargaining solution.

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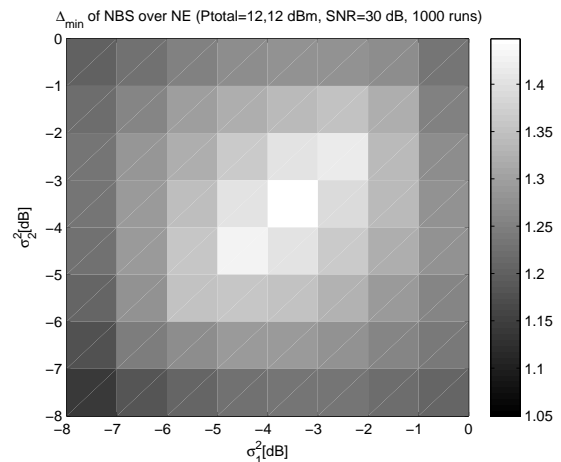[5] G. Owen, *Game theory*. Academic Press, third ed., 1995.

Fig. 1. Minimum relative gain of NBS over IWF, for SNR=30 dB, for various values of SINR.
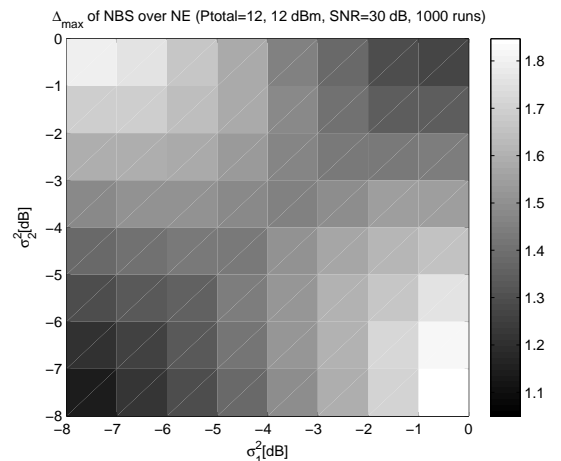

Fig. 2. Maximum relative gain of NBS over IWF, for SNR=30 dB, for various values of SINR.

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