A Joint Modulation, Rate, and Power Control Game-Theoretic Approach for Uplink CDMA Communications

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***Abstract*—**This work proposes a non-cooperative joint modulation, rate, and power control game-theoretic approach for the uplink of a single cell CDMA system. A generalized approach towards adaptive modulation is introduced, by fitting different efficiency functions of several modulations by means of the Gompertz sigmoid functions. The existence of a Nash equilibrium as well as the best response strategies for our game are then derived. An iterative algorithm to select the best power and rate values for the desired modulation is presented, reaching the equilibrium in a distributed manner. Each user maximizes its own utility satisfying minimum quality-of-service (QoS) requirements. Performance analysis is finally carried out in comparison with conventional joint rate and power control approach, also based on game theory.

***Index Terms*—**Adaptive modulation, power control, rate control, non-cooperative games, Nash Equilibrium.

I. Introduction

The key to the success of next-generation mobile communication systems is the ability to provide seamless interactive real-time multimedia services, satisfying applications' quality of service (QoS) requirements, while efficiently using the radio spectrum [1]. The available wireless spectrum is a limited resource and the need for spectrally efficient systems has motivated the development of adaptive transmission techniques, several of which are yet to be standardized [2]. These procedures adapt some of the users' parameters according to the communication channel conditions, signal-to-interference-plus-noise ratio (SINR), rate requirements, bit error rate (BER) needs, and battery constraints. In fact, while varying the data rates has the goal to improve the QoS of the real-time transmission, the power control contributes to extend the battery life of the mobile terminals [3].

In the context of (wide-band) direct-sequence code division multiple access (DS-CDMA) wireless networks, power control has traditionally been the single most important adaptation parameter and has been thoroughly studied (see [4] and references therein). Recent efforts on adaptation in CDMA networks have also focused on adapting the transmission rate using different strategies, such as: multiple codes [5]; adaptive modulation and coding (AMC) [6], and conventional variable processing gain (VPG) techniques [7], in which both the transmission power and data rate are adapted, but the modulation and coding are fixed. Rate adaption and power control in wireless networks are strictly connected each other: rate control regulates the source rates to avoid overwhelming any link capacity which depends on interference levels, which are in turn adjusted by power control policy [8]. Providing flexible transmission rates for each transmitter/receiver pair, as well as an efficient use of the shared radio spectrum, require joint power and rate control optimization algorithms [9]. Game theory was shown to be an appropriate tool for finding both power and rate flow control algorithms [10]. Different game models (e.g., non-cooperative/cooperative, static/dynamic, and complete/incomplete information games) have been developed to study the behavior of transmitting nodes to access the wireless channel(s) and obtain the multiple access solution (i.e. the equilibrium) [11]. The common aim of these models is to improve network performance (e.g., throughput maximization, resource consumption minimization, and QoS guarantee) given self-interest or group rationality of transmitting nodes [11]. The idea is to define for each user a function, namely the *utility function*, to be maximized according to some networks characteristics. For power control, the utility function usually depends on both the signal-to-interference ratio (SIR) and the transmission power of the terminal [12]-[15]. For joint rate and power control, the utility function must take into account also that each user is capable of variable transmission rates [16]. In particular, the authors in [16] formulate a non-cooperative joint transmission rate and power control game (NRPG) to determine the optimal rate and power of the transmission, maximizing the utility function of each user. Nevertheless joint rate and power control has proved to be a successful tool to efficiently use the limited spectrum resources, adaptive modulation has been shown to be an effective method for improving the spectral efficiency in wireless networks as well (see [17], [18], [19]). The authors in [17] propose a general framework to study the performance of adaptive modulation in cellular systems, while [18] considers modulation optimization for an energy constrained time-division-multiple-access (TDMA) network. In a recent development, the authors of [19] study the effects of modulation order on energy efficiency of wireless networks using a game-theoretic framework.

This paper proposes a non-cooperative joint modulation, rate, and power control game (NMRPG) defining an adaptive utility function which can link modulation, rate and power control. We exploit the Gompertz sigmoid functions [20] to fit different

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efficiency functions, proposing a generalized approach that takes into account several modulations. Here, we first sustain the preliminary results presented in [21] with extended simulation trials. Then, we move further by proposing and discussing a theoretical framework for our approach. In fact, since users are selfish and rational, a non-cooperative game is here proposed, in which each user can choose the transmit power and data rate as well as the modulation type in order to maximize its own utility. The existence of the Nash equilibrium is discussed and an iterative algorithm is proposed to update transmission rates, powers and modulation types jointly. Our numerical results are matched with the ones obtained in conventional NRPG approaches [16].

The remainder of this paper is organized as follows. In Section II, the system model is depicted as well as the utility function of the conventional NRPG approach. In Section III, our new utility function (linking modulation, rate and power control) is first derived and then the existence of a Nash equilibrium for our game is investigated. Section IV discusses the proposed iterative algorithm and its convergence, while our numerical results and comparisons are outlined in Section V. Finally, our conclusions are depicted in Section VI.

II. System Description

A. System Model

Let us consider the uplink communication of a single cell CDMA system with N mobile users that transmit data to the base station. It is well known (see [15]) that the SINR corresponding to the j-th user in the cell can be expressed as follows:

$$\gamma_j = \frac{B_W}{r_j} \cdot \frac{h_j \cdot p_j}{\sum_{\substack{k=1\\k\neq j}}^{N} h_k \cdot p_k + \sigma^2} \tag{1}$$

where B_W is the available spread-spectrum bandwidth, h_j is the set of path gains from the j-th mobile user to the base station, p_j is the power and r_j the transmission rate respectively of the j-th user, while σ^2 is the power spectral density of the additive white Gaussian noise (AWGN). The SINR expression of (1) assumes that in the CDMA system the users are assigned pseudorandom signature sequences and perform conventional matched filtering operations [15]. Since the available bandwidth B_w is shared among all the N users of the same cell, the transmission of the j-th user causes interference to the transmission of the other N-1 users. As a consequence, eq. (1) represents an indicator of the QoS (i.e. an indicator of the satisfaction of j-th user in transmitting at a given power and rate). Since most of the terminals in a wireless network are battery-powered, satisfying the QoS requirements while maintaining low energy consumption is very critical for the system performance, in fact energy efficiency has a direct impact in prolonging the life of the terminals. Users should achieve the satisfactory QoS level transmitting at the minimum power, given rate and SINR values. Clearly, higher SINR levels at the output of the receiver correspond to lower BER and obviously higher throughputs. Conversely, achieving a high SINR level often requires the user to transmit at a high power which in turn results in low battery life. This tradeoff can be captured by defining the utility (or payoff) function of a user as the ratio of its throughput (T_j) to the transmit power as follows:

$$u_j = \frac{T_j}{p_j} \tag{2}$$

B. Joint rate and Power Control

In a NRPG-theoretic approach, the utility function introduced in (2) can be explicitly expressed (in bits/Joule) in terms of rate and power of the j-th user as follows [16]:

$$u_j\left(r_j, p_j\right) = \frac{L \cdot r_j \cdot f\left(\gamma_j\right)}{M \cdot p_j} \tag{3}$$

where L is the number of information bits transmitted in a packet of length M and $f(\gamma_i)$ is the efficiency function, or frame success rate (FSR), expressed by:

$$f\left(\gamma_j\right) = \left(1 - P_e\right)^M \tag{4}$$

and evaluated for a fixed BER equal to P_e. Eq. (4) has been originally introduced in [13] to express the FSR of non-coherent frequency shift keying (NC-FSK) modulations. Then, the authors in [13] have also introduced an approximation of (4), to work with a well-behaved utility function, and expressed as follows:

$$f\left(\gamma_j\right) = \left(1 - 2 \cdot P_e\right)^M \tag{4b}$$

This means that eq. (4b) has the following properties: $f(\infty) = 1$ and $f(\gamma_j)$ / $p_j = 0$ for $p_j = 0$. In the following of this work, we have denoted with NC-FSK the modulation whose FSR is expressed by (4), and with NC-FSK-2 the modulation whose FSR is approximated by means of (4b). Usually, NC-FSK modulations are considered for both their low implementation complexity and low energy consumption [16]. The BER of this kind of modulation is expressed by:

$$P_e = \frac{1}{2} e^{-\gamma_j/2} \tag{5}$$

Then, the SINR of the j-th user γ_j can be rewritten in terms of rate and power by means of the following:

$$\gamma_j = c_j \frac{p_j}{r_j} \tag{6}$$

where the quantity:

$$c_j = \frac{B_W \cdot h_j}{\sum_{\substack{k=1\\k\neq j}}^{N} h_k \cdot p_k + \sigma^2} \tag{7}$$

does not depend on the rate and power of the j-th user. The goal of each user is hence to modify and adaptively update rate and transmission power in a distributed fashion in order to obtain the maximum payoff (i.e. so that the utility function of each user is maximized). The utility function of the conventional NRPG approach can be finally expressed as:

$$u_j\left(r_j, p_j\right) = \frac{L}{M}\frac{r_j}{p_j} f\left(\gamma_j\right) \qquad \text{(NRPG)} \qquad (8)$$

III. JOINT MODULATION, RATE AND POWER CONTROL

A. Utility Function

In order to relate the type of modulation to the utility function expressed by (8), at a first glance one could think to use the efficiency function expressed in (4), each time changing eq. (5): i.e. each time changing the formula that relates BER and SINR according to the considered modulation scheme. Hence, a NMRPG approach could be considered as the ensemble of all the NRPG schemes (each one with a different modulation kind), whose efficiency and utility functions are respectively defined by (4) and (8). Conversely, we are not interested here in schemes that are aggregated solutions of simple strategies. We aim at defining a non-cooperative and unitary strategic game characterized by a unique utility function, jointly relating modulation, rate and power control: we aim at proposing a generalized approach towards adaptive modulation. The high complexity of this kind of approach is represented by the fact that each modulation is characterized by a different efficiency function.

However, these functions are all characterized by a similar trend: in fact, they can be very well described by sigmoid functions, i.e. by S-shaped curves. An increasing function is S-shaped if there is a point above which the function is concave, and below which the function is convex [1]. We have decided to exploit the Gompertz sigmoid curves to fit these efficiency functions, since they are used to model time series, where growth is slowest at the start and end of a time period [20]. Moreover, Gompertz functions are usually adopted also in other research fields, such as in medicine to fit data of growth of tumors [22], in engineering management for financial forecasting [23], and in communications to model the mobile user growth [24]. A Gompertz function is defined as follows:

$$y(t) = a \cdot e^{b \cdot e^{\alpha(t-\beta)}} \qquad (9)$$

where a is the upper asymptote, b sets the abscissa displacement, while α sets the growth rate or the abscissa scaling, and β represents the horizontal shift [25]. In the case of our interest, we have approximated the FSR of each modulation exploiting the following Gompertz function:

$$f\left(\gamma_j\right) = e^{-e^{-\alpha\left(\gamma_j - \beta\right)}} \qquad (10)$$

with a = 1, b = -1, while the two parameters α and β are tuned to obtain the FSR of several modulations.

We have obtained a unified framework to express several utility functions by means of only one equation. Moreover, for each modulation kind, there is only one value of the SINR maximizing the utility function of that user, i.e. specifying the operating SINR γ_m, completely specifies the utility function. It is important to underline that γ_m is (uniquely) determined by physical-layer parameters (e.g. packet size, coding, …) [21]. In other words, the j-th user will always choose the modulation that allows maximizing its satisfaction and then, the terminal will properly set, for that modulation, the best values of power and rate as explained in details in Section IV.

B. Formulation as a Non-Cooperative Game

Usually, a non-cooperative rate and power control game can be defined as follows [1]:

$$G = \left[\mathbf{N}, \left\{A_j\right\}, \left\{u_j\right\}\right] \qquad (11)$$

where $\mathbf{N}$ = {1, …, N} represents the set of users/players, $\mathcal{A}_j$ is the strategy set for the j-th user, while $\boldsymbol{u}_j$ is its utility function defined by (8). Each user decides which strategy choose from its strategy set (i.e. rate and power) in order to maximize its own utility (i.e. to obtain the maximum satisfaction). Here, we propose a non-cooperative joint modulation, rate and power control game in which the actions open to each user are the choice of transmit power and rate, as well as the choice of the modulation scheme. Our game can be formally defined as:

$$G = \left[\mathbf{N}, \left\{P_j, R_j, M_j\right\}, \left\{u_j\right\}\right] \qquad (12)$$

where P_j, R_j, and M_j represent the strategy sets in power, rate and modulation type, respectively. The utility function of the NMRPG we propose is now expressed as follows:

$$u_j\left(m_j, r_j, p_j\right) = \frac{L}{M} \cdot \frac{r_j}{p_j} \cdot e^{-e^{-\alpha\left(\gamma_j - \beta\right)}} \qquad \text{(NMRPG)} \qquad (13)$$

Then, the j-th user selects a rate $r_j \in R_j$, a power $p_j \in P_j$, and a modulation type $m_j \in M_j$ to maximize its utility function, with the following constraints[1]:

$$0 < r_j \le \overline{r}, \text{ and } 0 < p_j \le \overline{p} \qquad (14)$$

$$m_j \in \left\{0\left(BPSK\right), 1\left(QPSK\right), \ldots, \overline{m}\left(64-PSK\right)\right\} \qquad (15)$$

where $\overline{r}$, $\overline{p}$, and $\overline{m}$ represent, respectively, the maximum rate, the maximum power and the maximum allowed modulation scheme. In particular, the selected modulation scheme, i.e. the value of m_j, depends on the values α and β (see Table. I) used to fit the FSR of that modulation. In fact, we can write m_j in terms of the couple α and β, as follows:

$$m_j = \left(\alpha_j, \beta_j\right) \in \left\{\left(\alpha_{BPSK}, \beta_{BPSK}\right)?, \left(\alpha_{QPSK}, \beta_{QPSK}\right), \ldots, \left(\alpha_{64-PSK}, \beta_{64-PSK}\right)\right\} \qquad (16)$$

We can now show that for the utility function expressed by (13), a Nash equilibrium solution exists. In particular, using (6) in (13) and after some algebra, the utility function re-writes as follows:

$$u_j\left(\gamma_j\right) = \frac{L \cdot c_j}{M} \cdot \frac{1}{\gamma_j} \cdot e^{-e^{-\alpha\left(\gamma_j - \beta\right)}} \qquad (17)$$

where the utility function depends only on the variable γ_j. In fact, once the modulation scheme has been selected, the values α and β are considered as two constants for

[1] Note that the utility function is not defined for either $r_j = 0$ or $p_j = 0$.

that user, as well as the quantity c_j. Hence, the utility function can be expressed using (10) and (13) and as a function of γ_j, as follows:

$$u_j(\gamma_j) = \frac{f(\gamma_j)}{\gamma_j}, \quad \gamma_j \in \Gamma_j \quad \text{and} \quad \Gamma_j = \Re^+ \tag{18}$$

where Γ_j is the strategy set for γ_j.

There exists a Nash equilibrium for our proposed game NMRPG = [N, { Γ_j },{$u_j(\gamma_j)$}] if, $\forall j = 1, 2, ..., N$, the following two conditions are satisfied:

- Γ_j is a nonempty, compact, and convex set in Euclidean spaces (see the equilibrium theorem of Nikaido and Isoda [26]);
- $u_j(\gamma_j)$ is a continuous function in Γ_j and quasi-concave in γ_j.

The first condition is always true, since Γ_j is by definition a nonempty, compact, and convex set in Euclidean Space. Hence, to satisfy the second condition, we need to prove that the utility function $u_j(\gamma_j)$ can be derived in Γ_j, and has a unique maximizing point. Let us now evaluate the derivative of $u_j(\gamma_j) = \frac{f(\gamma_j)}{\gamma_j}$ with respect to γ_j and, after equating it to zero, we can conclude that the utility of the j-th user is maximized when $\gamma_j = \gamma_{max}$, where γ_{max} is the (positive) solution of $f(\gamma_j) = \gamma_j f'(\gamma_j)$, where $f'(\gamma_j)$ is the first derivative of $f(\gamma_j)$. It is shown in [27] that for an S-shaped (sigmoidal) efficiency function, $f(\gamma_j) = \gamma_j f'(\gamma_j)$ has a unique solution. As a consequence, our game admits Nash equilibria.

Finally, it has to be noted the uniqueness of our Nash equilibrium solution: the Nash equilibrium depends on the initial choice about powers and rates. Moreover, if the initial choice of rates and powers is changed, then a different Nash equilibrium point may be reached.

IV. The Adaptive Modulation Algorithm

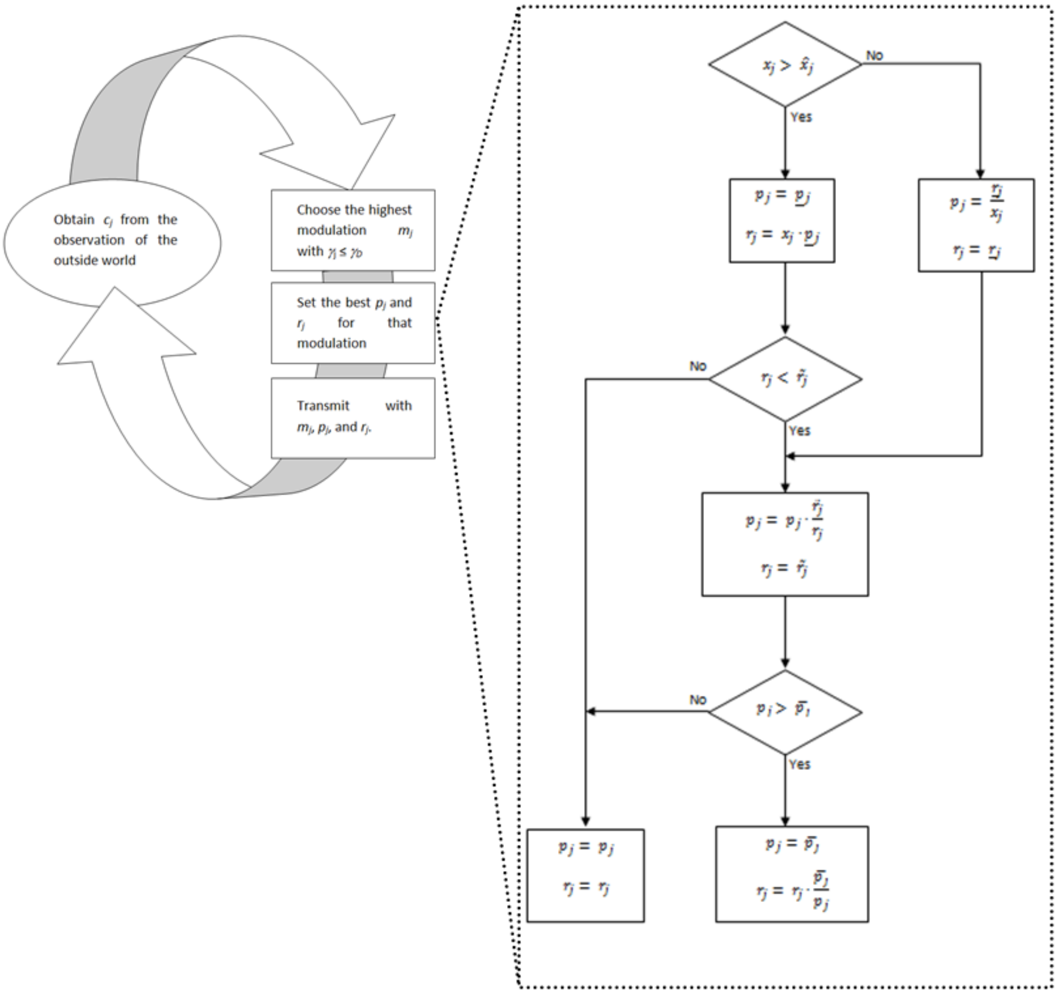

Fig. 1. The diagram illustrates: *left)* the entire procedure to update modulation, rate and power in each terminal; *right)* the detailed joint rate and power control algorithm.

In this Section, the iterative algorithm to select the correct values of modulation, rate and power is illustrated. Referring to Fig. 1, the users iteratively update rates and powers asynchronously such that for a given user the new rate and power values are computed in the same step. In particular, the left side of Fig. 1 depicts the entire procedure, starting from the observation of the external world to obtain the knowledge of the interference plus noise experienced by user j's signal at the base station (i.e. c_j), then using this value to choose the best modulation, and finally setting the best power and rate for that modulation. According to Fig. 1, the first step to be realized is represented by the modulation choice, knowing the value of c_j. To this aim, let us now define $x_d = r_d / p_d$ as the ratio between the values of rate r_d and power p_d desired by the j-th mobile terminal to satisfy its minimum QoS requirements. Now, the quantity $\gamma_d = c_j / x_d$ represents the maximum obtainable SINR of the j-th terminal with respect to the external interference (represented by c_j) and at the minimum QoS. With the aim to obtain the maximum satisfaction, the j-th terminal must choose a modulation whose γ_m is the nearest one to (but less than) the maximum available γ_d: this means that (considering c_j as a constant for the j-th user) if $\gamma_m \leq \gamma_d$, then $x_j \geq x_d$. As a consequence, the j-th terminal can now increment the available transmission rate or decrease the maximum required power, guaranteeing the same QoS constraints.

The detailed joint rate and power control algorithm is illustrated in the right side of Fig. 1, where $\tilde{r}_j$ is the minimum required data rate (RDR) for the j-th mobile terminal (i.e. the rate required to satisfy the QoS of that terminal) and $\hat{x}_j = \frac{r_j}{p_j}$ is the ratio between the minimum rate and power for that terminal. Obviously, if the minimum value for the rate is $\underline{r}_j = 0$, then $\hat{x}_j = \underline{x}_j = 0$. The rationale of the algorithm is as follows:

- In the first step, the algorithm tries to determine the value of the rate when the power is at a minimum. In particular, if $x_j > \hat{x}_j$ then the power is kept at a minimum, and the rate is increased accordingly. Otherwise, the rate is kept fixed, and the power is increased.
- In the second step, if the previously determined rate is below the RDR, both the rate and power will be increased accordingly (if in the first step the rate was the minimum rate, it is obviously below the RDR). Otherwise, the current values of rate and power are chosen for the transmission phase.
- In the third step, the algorithm verifies that the previously incremented power is under the maximum allowed value, otherwise the transmitting power is chosen equal to the maximum value. Finally, the best values of power and rate have been selected and then used for the transmission, maximizing the utility function of the chosen modulation scheme.

V. Numerical Results

Several simulation trials were performed to validate the proposed approach (derived in the previous sections). In particular, we have considered a single cell uplink CDMA system and compared it with the rate and power control algorithm described in [16] which we refer to as the NRPG algorithm. The system parameters are as follows:

- The distances (in meters) of the mobile users around the base station use the vector [50, 100, 150, 200, 250, 300, 350, 400, 450, 500], as done in [16].
- All users are assumed to be stationary.
- The propagation model has channel gains, h_j, that are inversely proportional to the 4th power of the distance d_j^4 (in meters) from the base station: $h_j = c / d_j^4$, where c = 0.097 is a constant.
- The power spectral density of the AWGN at the receiver is $\sigma^2 = 5 \times 10^{-15}$ W/Hz.
- The minimum and maximum powers of each user are $\underline{p} = 10^{-6}$ W and $\overline{p} = 0.2$ W, respectively.
- The minimum and maximum transmission rates of each user are $\underline{r}$ = 0.1 [bits/sec] and $\overline{r}$ = 96000 [bits/sec], respectively.

First of all, let us now focus on the convergence behavior of the proposed algorithm, considering (for the sake of simplicity) only 5 users on 10 (but the results are the same for the other users). Fig. 2 illustrates the number of required iterations needed by the users to reach the convergence point. Clearly and as evident from Fig. 2, users number 1, 2, and 3 (near to the base station) can reach the equilibrium using less power than users number 8 and 10 (that are the farthest users from the base station).

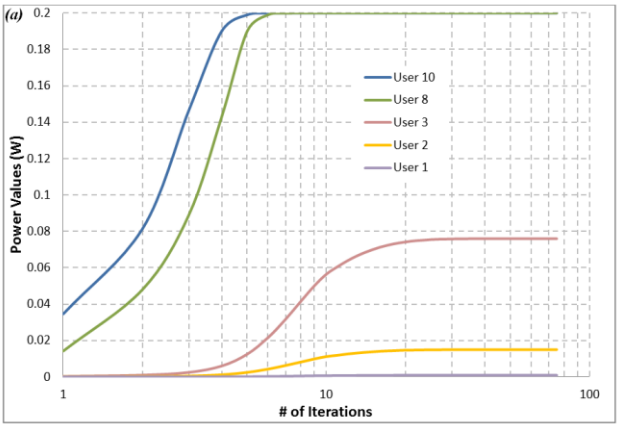

Fig. 2. Convergence behavior of the proposed adaptive modulation game in terms of Power values.

In terms of power, this means that farther distances correspond to higher users' transmitting powers. Similarly, the same happens in terms of rate. In fact, user number 1 (that is the nearest to the base station) can transmit with the maximum allowed rate (equal to 9.6 kbit/s), while the rate of the other users decreases proportionally to the user's distance from the base station. It is interesting to note that the proposed method takes about 10-60 iterations to converge to the equilibrium. These results are perfectly matched to the ones presented in [16], where it is demonstrated that the conventional NRPG approach needs about 20-60 iterations to converge. This means that the proposed method (with adaptive modulation) presents the same computational complexity (i.e. the same convergence speed) of the conventional approach (implemented with a fixed modulation scheme).

Then, let us now compare the performances of these two methods. In particular, the comparison is made using operating scenarios, characterized by different available bandwidths (from 3.84 MHz, to 5.4 MHz and 7.86 MHz). Fig. 3 reports the values of the transmitted power while

Fig. 4 shows the values of data rates of each user obtained with the two analyzed methods, respectively.

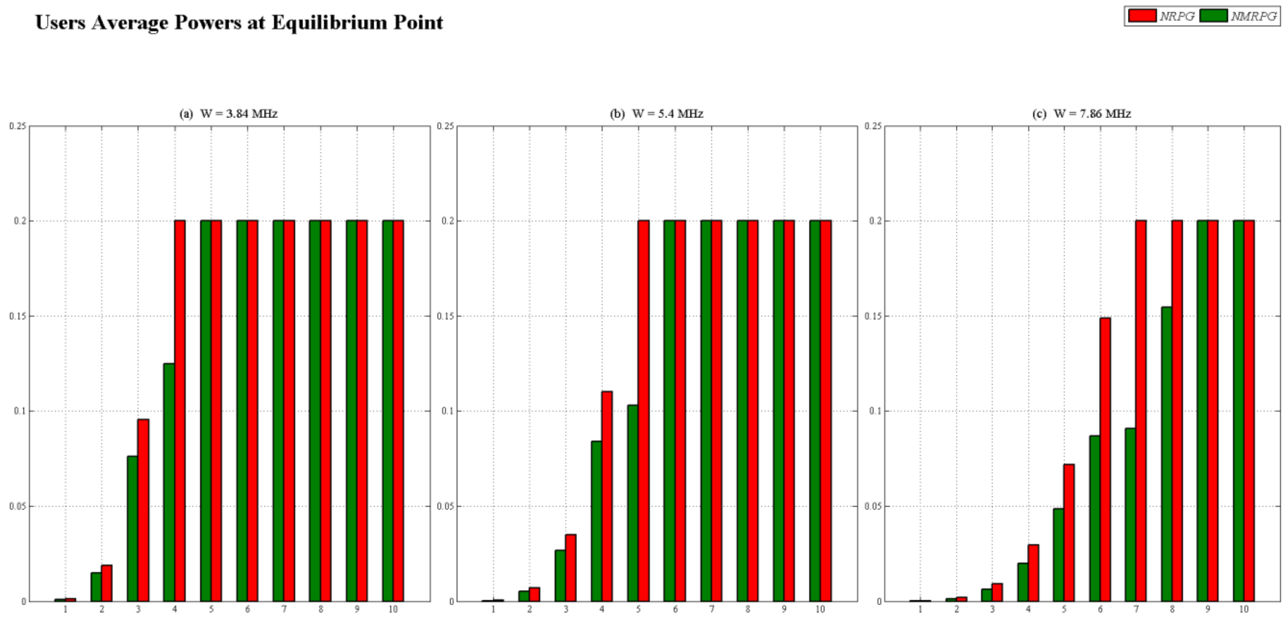

Fig. 3. Powers at the equilibrium obtained by the NRPG and our NMRPG approach for: *a)* W = 3.84 MHz, *b)* W = 5.4 MHz, *c)* W = 7.86 MHz.

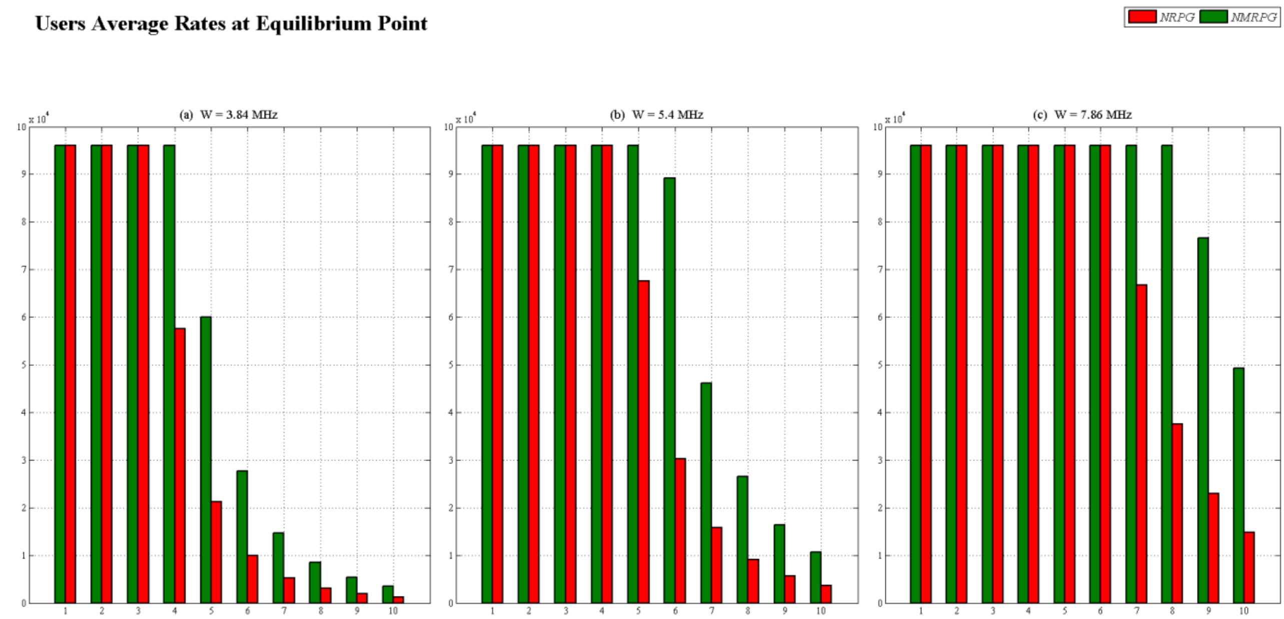

Fig. 4. Rates at the equilibrium obtained by the NRPG and our NMRPG approach for: ***a)*** W = 3.84 MHz, ***b)*** W = 5.4 MHz, ***c)*** W = 7.86 MHz.

User number 1 is the closest to and user number 10 is the farthest from the base station. In particular, Fig. 3a and Fig. 4a illustrates the powers and rates for *W* = 3.84 MHz, while Fig. 3b and Fig. 4b show the scenario with *W* = 5.4 MHz, and finally Fig. 3c and Fig. 4c represent the case of *W* = 7.86 MHz. Users closer to the base station are characterized by similar powers and rates, transmitting at higher rates and lower powers than users farther away from the base station. It has to be underlined that the proposed game (with adaptive modulation) allow the users to reach higher data rates and lower powers (see for example users 3, 4, and 5) than the ones obtained with the conventional rate and power control game. It is interesting to note that, for both the considered approaches, when the available bandwidth *W* increases, the number of users transmitting at the maximum allowed power and/or minimum allowed rate decreases. Moreover, our proposed game results in more efficient power and rate allocations than the conventional scheme in all the presented cases.

Finally, in order to prove the efficiency of the joint modulation, rate and power control game, we have depicted in Fig. 5 the utility of each user at the equilibrium, for both the considered algorithm, and again for different bandwidths. Again, user number 1 is the closest to while user number 10 is the farthest from the base station In particular, Fig. 5a shows the case of W = 3.84 MHz, Fig. 5b the scenario with W = 5.4 MHz, and finally Fig. 5c illustrates the utility at the equilibrium for an available bandwidth W = 7.86 MHz. It can be easily seen that, while users closer to the base station can reach almost the same satisfaction with the two methods, users far from the base station can achieve higher level of utility exploiting the advantage of adaptive modulation. This is due to the fact that these users can achieve lower values of transmitting powers and/or higher values of data rates accordingly changing the type and size of their constellation

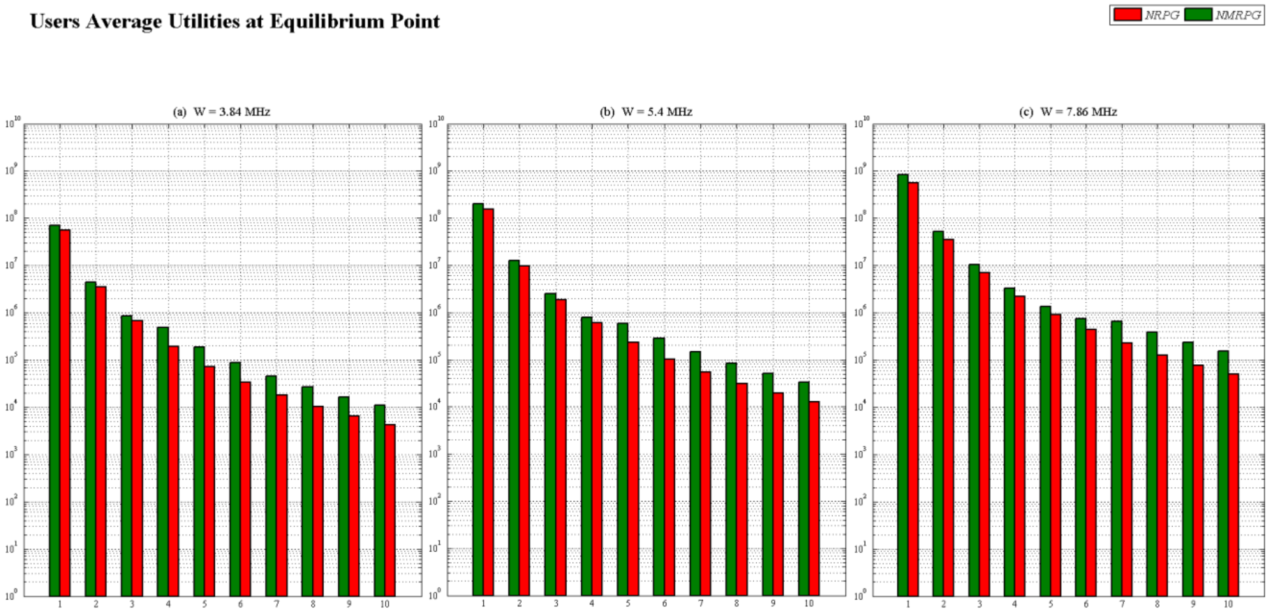

Fig. 5. Utility values at the equilibrium obtained by the NRPG and our NMRPG approach for: *a)* W = 3.84 MHz, *b)* W = 5.4 MHz, *c)* W = 7.86 MHz.

VI. Conclusion

This paper has addressed the problem on design and analysis of a non-cooperative joint modulation, rate, and power control game-theoretic approach for the uplink of a single cell CDMA system. A generalized approach towards adaptive modulation has been introduced, exploiting the Gompertz sigmoid functions. A non-cooperative game has been proposed, in which each user can choose the transmit power and data rate as well as the modulation type in order to maximize its own utility. Performance analysis has been carried out in comparison with conventional joint rate and power control approach, also based on game theory. Our numerical results show the effectiveness of the proposed approach for application to the uplink of a single cell CDMA system, determining the optimal modulation, rate, and transmitting power of each user.

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