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Application of Game Theory in Ad- hoc Opportunistic Radios

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Abstract **The application of mathematical analysis to the study of wireless ad hoc networks has met with limited success due to the complexity of mobility, traffic models and the dynamic topology. A scenario based UMTS TDD opportunistic cellular system with an ad hoc behaviour that operates over UMTS FDD licensed cellular network is considered. In this paper, we describe how ad hoc opportunistic radio can be modeled as a game and how we apply game theory based Power Control in ad-hoc opportunistic radio.**

Keyword: *Opportunistic Radios, Game theory, UMTS, ad-hoc network.*

I. INTRODUCTION

A wireless ad hoc network is characterized by a distributed, dynamic, self-organizing architecture. Each node in the network is capable of independently adapting its operation based on the current environment according to predetermined algorithms and protocols. Analytical models to evaluate the performance of ad hoc networks have been scarce due to the distributed and dynamic nature of such networks. Game theory offers a suite of tools that may be used effectively in modeling the interaction among independent nodes in an ad hoc network [8].Here we assume a cognitive radio 'is a radio that can change its transmitter parameters based on interaction with the environment where it operates' [1], and additionally relevant here is the radio's ability to look for, and intelligently assign spectrum 'holes' on a dynamic basis from within primarily assigned spectral allocations. The detecting of holes and the subsequent use of the unoccupied spectrum is referred to as opportunistic use of the spectrum. An Opportunistic Radio (OR) is the term used to describe a radio that is capable of such operation [2].In this paper we use the opportunistic radio system which was proposed in [3] that shares the spectrum with an UMTS cellular network. This is motivated by the fact that UMTS radio frequency spectrum has become, in a significant number of countries, a very expensive commodity, and therefore the opportunistic use of these bands could be one way for the owners of the licenses to make extra revenue.
The OR system exploits the UMTS UL bands, therefore, the victim device is the UMTS base station, likely far from the opportunistic radio, whose creates local opportunities. These potential opportunities in UMTS FDD UL bands are in line with the interference temperature metric proposed by the FCC s Spectrum Policy Task Force [4]. The interference temperature model manages interference at the receiver through the interference temperature limit, which is represented by the amount of new interference that the receiver could tolerate. As long as OR users do not exceed this limit by their transmissions, they can use this spectrum band. However, handling interference is the main challenge in CDMA networks, therefore, the interference temperature concept should be applied in UMTS licensed bands in a very careful way. In this paper we propose how an ad hoc behaviour uses in an opportunities radio and with careful selections of routing schemes, we minimize overall interference level on the victim device UMTS base station.
This paper is organized as follows: In Section II the scenario is defined. Section III explains the opportunistic network with ad-hoc topology. Section IV explains the game theory in opportunistic radios. Section V explains the use of game theory in opportunistic network and section VI describe OR power control using game theory, followed by the conclusion.

II. SCENARIO DEFENITION

The UMTS is a DS-CDMA system, thus all users transmit the information spreaded over 5 MHz bandwidth at the same time and therefore users interfere with one another. Figure 1 shows a typical UMTS FDD paired frequencies. The asymmetric load creates spectrum opportunities in UL bands since the interference temperature (amount of new interference that the UMTS BS can tolerate) is not reached.

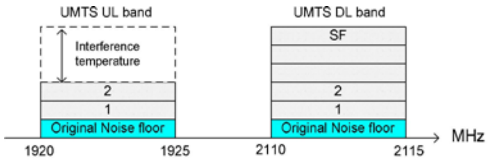

Figure 1: UMTS FDD spectrum bands with asymmetric load

In order to fully exploit the unused radio resources in UMTS, the OR network should be able to detect the vacant channelization codes using a classification technique [5].Thus the OR network could communicate using the remaining spreading codes which are orthogonal to the used by the UMTS network. However, classify and identify CDMA's codes is a very computational intensive task for real time applications. Moreover, synchronization between UMTS UL signals and the OR signals to keep the

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ortogonality between codes will be a difficult problem. Our approach is to fill part of the available interference temperature raising the noise level above the original noise floor. This rise is caused by the OR network activity, which aggregated signal is considered AWGN (e.g CDMA, MC-CDMA, OFDM).We consider a scenario where the regulator allows a secondary cellular system over primary cellular networks. Therefore we consider opportunistic radios entities as secondary users. The secondary opportunistic radio system can use the licensed spectrum provided they do not cause harmful interference to the owners of the licensed bands i.e., the cellular operators.Specifically we consider as a primary cellular network an UMTS system and as secondary networks an ad hoc network with extra sensing features and able to switch its carrier frequency to UMTS FDD frequencies. Figure 2 illustrates the scenario where an opportunistic radio network operates within an UMTS cellular system. We consider an ah hoc OR network of M nodes operating overlapped to the UMTS FDD cell. The OR network acts as a secondary system that exploit opportunities in UMTS UL bands. The OR network has an opportunity management entity which computes the maximum allowable transmit power for each OR node in order to not disturb the UMTS BS.

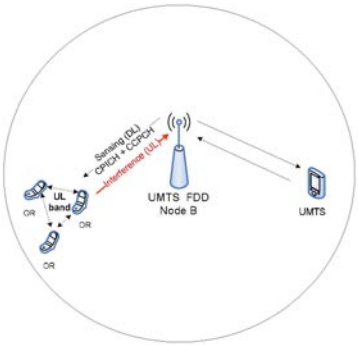

Figure 2: Ad hoc ORs networks operating in a licensed UMTS UL band

III. THE OPPORTUNISTIC NETWORK WITH AD HOC TOPOLOGY

The opportunistic network, showed in Figure 3, will interface with the link level simulator through LUTs. The propagation models developed for the UMTS FDD network will be reused, and the entire channel losses (slow and fast fading) computed. The outputs will be the parameters that usually characterize packet transmissions: Throughput, BLER and Packet Delay. The LUT sensing algorithm characterization block contains the cyclostationary detector's performance, i.e. the output detection statistic, *d*, as a function of the SNR measured at the sensing antenna for different observation times [6]. The sensing OR-UMTS path loss block estimates the path loss between UMTS BS and the OR location through the difference between the transmitted power and the estimated power given by cyclostationary detector (LUT sensing algorithm characterization block output). The OR traffic generation block contains real and non-real time service traffic models OR QoS block defines the minimum data rate, the maximum bit error rate and the maximum transmission delay for each service class The non-interference rule block compute the

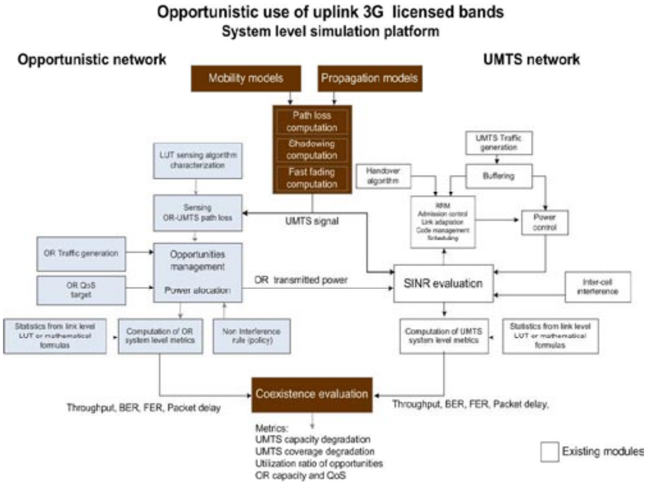

Figure 3: Block diagram of the system level platform

maximum allowable transmit power without disturbing the UMTS BS applying a simple non-interference rule (according to policy requirements).In the following, we briefly explain the opportunistic network blocks that was designed and implemented, using a C++ design methodology approach.

First of all, we assume that the OR knows a priori the UMTS carrier frequencies and bandwidths, which has been isolated and brought to the baseband. In order to get the maximum allowable power for OR communications the OR nodes need to estimate the path loss from its location to the UMTS BS, i.e., the victim device. The opportunistic user is interested in predefined services which should be available every time. This motivates the proposal of defining a set of usable radio front end parameters in order to support the demanded services classes under different channel conditions. Basically, at the beginning of each time step the opportunistic radio requires certain QoS guarantees including certain rate, delay and minimum interference to the primary user (non interference rule policy).

The opportunistic network has an opportunity management entity which computes the maximum allowable transmit power for each opportunistic node in order the aggregated interference do not disturb the UMTS BS. The aggregated transmit power allowed to the opportunistic network can be computed using a simple non-interference rule

$$10\log\left(\sum_{k=1}^{K} 10^{\frac{P_{OR}(k)+G_{OR}+G_{BS}-\hat{L}p(k)}{10}}\right) \le 10\log\left(10^{\frac{Nth+\mu}{10}} - 10^{\frac{Nth}{10}}\right) - \Gamma$$

Where G_{OR} is the OR antenna gain, G_{BS} is the UMTS BS antenna gain, *Lp* is the estimated path loss between the OR node and the UMTS BS, *K* is the Number of ORs, performed by a sensing algorithm, and *Nth* is the thermal noise floor. μ is a margin of tolerable extra interference that, by a policy decision, the UMTS BS can bear. Finally, Γ is a safety factor to compensate shadow fading and sensing s impairments. Notice if the margin of tolerable interference μ=0 the OR must be silent. Γ is a safety factor margin (e.g. 6-10 dB) to compensate the mismatch between the downlink and uplink shadow fading and others sensing's impairments. The margin of tolerable interference is defined according to policy requirements.
Employing scheduling algorithms, we can provide a good tradeoff between maximizing capacity, satisfying delay constraint, achieving fairness and mitigating interference to the primary user. In order to satisfy the individual QoS constraints of the opportunistic radios, scheduling algorithms that allow the best user to access the channel based on the individual priorities of the opportunistic radios, including interference mitigation, have to be considered. The objective of the scheduling rules is to achieve the following goals:

- Maximize the capacity;
- Satisfy the time delay guarantees;
- Achieve fairness;
- Minimize the interference caused by the opportunistic radios to the primary user.

A power control solution is required to maximize the energy efficiency of the opportunistic radio network, which operates simultaneously in the same frequency band with an UMTS UL system. Power control is only applied to address the non-intrusion to the services of the primary users, but not the QoS of the opportunistic users.
A distributed power control implementation which only uses local information to make a control decision is of our particular interest. Note that each opportunistic user only needs to know its own received SINR at its designated receiver to update its transmission power. The fundamental concept of the interference temperature model is to avoid raising the average interference power for some frequency range over some limit. However, if either the current interference environment or the transmitted underlay signal is particularly non uniform, the maximum interference power could be particularly high.

IV. GAME THEORY IN OPPORTUNISTIC RADIO NETWORKS

A wireless ad hoc network is characterized by a distributed, dynamic, self-organizing architecture. Each node in the network is capable of independently adapting its operation based on the current environment according to predetermined algorithms and protocols. So, we are choosing analytical models to evaluate the performance of ad hoc networks with opportunists radio access have been scarce due to the distributed and dynamic nature of such networks. Game theory offers a suite of tools that may be used effectively in modeling the interaction among independent OR nodes in an ad hoc network
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Game theory
Game theory is a field of applied mathematics that describes and analyzes interactive decision situations. It provides analytical tools to predict the outcome of complex interactions among rational entities, where rationality demands strict adherence to a strategy based on perceived or measured results. The main areas of application of game theory are economics, political science, biology and sociology. From the early 1990s, engineering and computer science have been added to this list. We limit our discussion to non-cooperative models that address the interaction among individual rational decision makers. Such models are called "games" and the rational decision makers are referred to as "players." In the most straightforward approach, players select a single action from a set of feasible actions. Interaction between the players is represented by the influence that each player has on the resulting outcome after all players have selected their actions. Each player evaluates the resulting outcome through a payoff or "utility" function representing its objectives.
There are two ways of representing different components (players, actions and payoffs) of a game: normal or strategic form, and extensive form. Here we will focus on the normal form representation.
Formally, a normal form of a game *G* is given by

$$G = \{ N, A, \{u_i\} \}$$

where $N=\{1,2,...,n\}$ is the set of players (decision makers), A_i is the action set for player *i*,
$A = A_1 \times A_2 \times,...,\times A_n$ is the Cartesian product of the sets of actions available to each player, and $\{u_i\}=\{u_1,..., u_n\}$ is the set of utility functions that each player *i* ,wishes to maximize, where $u_i : A \to \mathbf{R}$. For every player *i*, the utility function is a function of the action chosen by player *i*, a_i and the actions chosen by all the players in the game other than player *i*, denoted as $\mathbf{a}_{-i}$ .Together, a_i and $\mathbf{a}_{-i}$ make up the action tuple $\mathbf{a}$. An action tuple is a unique choice of actions by each player. From this model, steady-state conditions known as *Nash equilibria* can be identified. Before describing the Nash equilibrium we define the best response of a player as an action that maximizes its utility function for a given action tuple of the other players. Mathematically, $\bar{a}$ is a best response by player *i* to $\mathbf{a}_{-i}$ if

$$\bar{a} \in \{\arg\ \max u_i\ (a_i, a_{-i})\}$$

Nash equilibrium (NE) is an action tuple that corresponds to the mutual best response: for each player *i*, the action selected is a best response to the actions of all others. Equivalently, a NE is an action tuple where no individual player can benefit from unilateral deviation. Formally, the action tuple

$\mathbf{a}^* = (a_1^*, a_2^*, a_3^*, ..., a_n^*)$ is a NE if $u_i(a_1^*, \mathbf{a}_{-i}^*) \geq (a_1^*, \mathbf{a}_{-i}^*)$ for all $\forall a_i \in A_i$ and for all $\forall i \in N$.

The action tuples corresponding to the Nash equilibria are a consistent prediction of the outcome of the game, in the sense that if all players predict that Nash equilibrium will occur then no player has any incentive to choose a different strategy. There are issues with using the Nash equilibrium as a prediction of likely outcomes (for instance, what happens when multiple such equilibria exist?). There are also refinements to the concept of Nash equilibrium tailored to certain classes of games. A detailed discussion of these is outside the scope of this deliverable. There is no guarantee that a Nash equilibrium, when one exists, will correspond to an efficient or desirable outcome for a game (indeed, sometimes the opposite is true). Pareto optimality is often used as a measure of the efficiency of an outcome. An outcome is Pareto optimal if there is no other outcome that makes every player at least as well off while making at least one player better off.
Mathematically, we can say that an action tuple
$\mathbf{a} = (a_1, a_2, a_3, ..., a_n)$ is Pareto optimal if and only if there exists no other action tuple
$\mathbf{b} = (b_1, b_2, b_3, ..., b_n)$ such that $u_i(\mathbf{b}) \geq (\mathbf{a})$ for $\forall i \in N$, and for some $k \in N$ $u_k(\mathbf{b}) \geq u_k(\mathbf{a})$.

V. USING GAME THEORY IN OPPORTUNISTIC NETWORKS

For over a decade, game theory has been used as a tool to study different aspects of computer and telecommunication networks, primarily as applied to problems in traditional wired networks. In the past three to four years there has been renewed interest in developing networking games, this time to analyze the performance of wireless ad hoc networks (ORs). Since the game theoretic models developed for ad hoc networks focus on distributed systems, results and conclusions generalize well as the number of players (ORs) is increased. It is also of interest to investigate how selfish behavior by individual nodes (ORs) may affect the performance of the UMTS system as a whole.In a game, players (ORs) are independent decision makers whose payoffs depend on other players' (OR) actions. Nodes (OR) in an ad hoc network are characterized by the same feature. This similarity leads to a strong mapping between traditional game theory components and elements of an ad hoc network. Table 1 shows typical components of an ad hoc networking game. Game theory can be applied to the modeling of an ad hoc network at the physical layer (distributed power control), link layer (medium access control) and network layer (packet forwarding). Applications at the transport layer and above exist also, although less pervasive in the literature. A question of interest in all those cases is that of how to provide the appropriate incentives to discourage selfish behavior. Selfishness is generally detrimental to overall network performance; examples include a node's increasing its power without regard for interference it may cause on its neighbors (layer 1), a node's immediately retransmitting a frame in case of collisions without going through a backoff phase (layer 2), or a node's refusing to forward packets for its neighbours (layer 3).

Table 1: Typical mapping of ad hoc network components to a game

Components of a game	Elements of an ad hoc network
Players	Nodes in the network
Strategy	Action related to the functionality Being studies(e.g. the decision to forward packets or not, the setting of power level, the selection of waveform/modulation scheme)
Utility function	Performance metrics(e.g. throughput, delay, target signal-to noise ratio)

VI. USING GAME THEORY FOR OR POWER CONTROL

Transmit-power control is necessary for the opportunistic radio system to broaden the scope of its applications and enhance the performance. It would have to operate under two limitations on network resources: the interference temperature limit imposed by regulatory agencies, and the availability of a limited number of spectrum holes depending on usage. In a multiuser opportunistic radio (ORs) environment, all the users operate in a decentralized manner; they are characterized by cooperation and competition. In such a case, game theory could be applied to exercise control over the transmit power. Distributed power control may be adopted by a node (OR). From a physical layer perspective, performance is generally a function of the effective signal-to-interference-plus-noise ratio (SINR) at the node(s) of interest. When the nodes in a network respond to changes in perceived SINR by adapting their signal, a physical layer interactive decision making process occurs. This signal adaptation can occur in the transmit power level and the signaling waveform (modulation, frequency, and bandwidth). The exact structure of this adaptation is also impacted by a variety of factors not directly controllable at the physical layer, including environmental path losses and the processing capabilities of the node(s) of interest. A game theoretic model for physical layer adaptations can be formed using the parameters listed in Table 2.

From Table 2 , the stage game for interactive physical layer adaptations can be modeled as
$G = \{ N, \{ \mathbf{P_j} \times \mathbf{\Omega_j} \}, \{u_j (\mathbf{P}, \boldsymbol{\omega}, H)\} \}$

For a general game, each OR node, j, selects a power level, p_j, and a waveform, ω_j, based on its current observations and decision making process. Distributed power control systems permit each OR radio to select p_j, but restrict $\mathbf{\Omega}_j$ to a singleton set; distributed waveform adaptation systems (interference avoidance) restrict the choice of p_j, but allow ω_j to be chosen by the physical layer.
Power control, though closely associated with cellular networks and is implemented in OR ad hoc network that operated in the same bands that the primary user UMTS system We now model the power control algorithm suggested in [9] as a normal form game. Note that a similar approach can be followed to model the other distributed algorithms as games, with each game involving a different utility function. We adopt the notation in Table 2
For most game models, the game theoretic equivalent of a distributed algorithm's steady state is a *Nash equilibrium* (NE). An action vector (or alternative vector) *a* is said to be a NE if equation (1) is satisfied.

$$u_i(\mathbf{a}) \geq u_i(b_i, a_{-i}) \; \forall \; i \in N, b_i \in N \qquad (1)$$

Consider a DS-CDMA system with a centralized receiver where all OR nodes other than the centralized receiver are adjusting their transmitted power levels in an attempt to maximize their signal-to interference- plus-noise ratio (SINR) as measured at the receiver. Here our set of players are the OR nodes (other than the centralized receiver); the action sets are the available power levels (presumably a finite number of power levels) all OR player's utility functions are given by equation (2)

$$u_i(\mathrm{p}) = h_i p_i \,/\, ((1/\mathrm{K}) \sum_{j \in N \setminus i} h_k \, p_k + \sigma) \qquad (2)$$

where p_i is the transmitted power of node i, K is the statistical estimate of the spreading factor, h_i is the gain from a node to the receiver, and σ is the noise at the receiver.

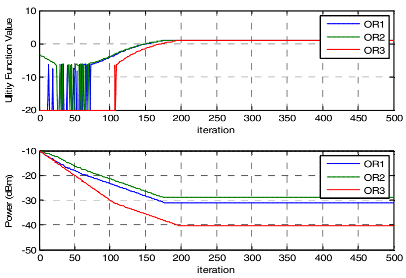

Figure 4: 3 OR node closer to the UMTS system

As would be indicated by intuition, the unique Nash equilibrium for this game is the power vector where all OR nodes transmit at maximum power. This is an undesirable outcome as (1) capacity is greatly diminished due to near-far problems (unless the nodes are all at the same radius from the receiver as shown in the Figure 4 and Figure 5 where OR node are closer and far away from the UMTS system), equation (2) the resulting SINRs are unfairly distributed (the closest node will have a far superior SINR(as shown in the Figure 4)

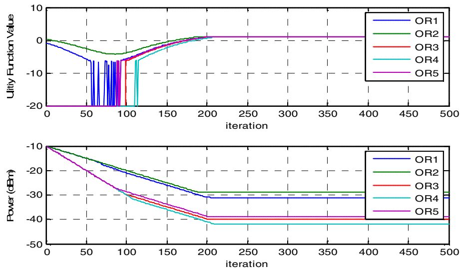

Figure 5: 5 OR node far away to the UMTS system

to the furthest node(as shown in the Figure 5 and (3) battery life would be greatly shortened. However, this outcome is Pareto optimal as any more equitable power allocation will reduce the utility of the closest node, and any less equitable allocation will reduce the utility of the disadvantaged nodes. In this scenario Pareto optimality actually misleads the analyst with respect to the desirability of the outcome.

VII. CONCLUSION

Emerging research in game theory based power control applied to ad hoc opportunist networks shows much promise to help understand the complex interactions between OR nodes in this highly dynamic and distributed environment. Also, the employment of game theory in modeling dynamic situations for opportunist ad hoc networks where OR nodes have incomplete information has led to the application of largely unexplored games such as games of imperfect monitoring. Ad hoc security using game theory is the future area of research in ORs

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