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Using Cooperative MIMO techniques to improve the Capacity of Wireless Networks - Simulation Perspective

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Abstract – The capacity of a wireless network is an important asset to be evaluated and optimized. An open and challenging research area is represented by evaluation of fundamental upper / lower bounds for data capacity region under the constraints of delay and outage limits. A cognitive radio network composed of a large number of adaptive mechanisms capable to take advantage of local radio conditions knowledge could be seen as the way to reach the optimum capacity figures. Cooperative MIMO techniques applied per cluster-area are seen as a representative local mechanism. Their impact over the wireless capacity would represent an important benchmark for network design improvements.

Keywords: cognitive radio network, cooperative MIMO, radio resource management, OFDM, channel model, wireless system capacity, wireless system simulation

I. INTRODUCTION

A peak data rate of 100 Mbit/s for high and 1 Gbit/s for low mobility is a challenging requirement which a radio access technology has to be able to provide in order to be accepted as an IMT-Advanced 4G solution [1] [2] [3]. At the same time there are a large variety of services with their respective Quality-of-Service (QoS) requirements which should be supported by the next generation wireless networks under the umbrella of fairness criteria among different mobile users. And above all, these high level requirements should be met under a variety of radio environments and deployments. Of today, two radio access technology (RAT) proposals are under evaluation of International Telecommunication Union (ITU) to become part of IMT-Advanced RATs, namely IEEE 802.16m WiMAX [4] and 3GPP LTE-Advanced [5]. Both of them rely among others on a set of common generic radio techniques as:

- Advanced antenna techniques as Multiple-Input Multiple-Output (MIMO) systems capable of providing diversity and/or array processing gains
- Increased granularity of time-frequency radio resources by means of Orthogonal Frequency Division Multiplexing (OFDM) technique with its adaptations Orthogonal Frequency Division Multiple Access (OFDMA) / Single Carrier – Frequency Division Multiple Access (SC-FDMA)
- IP-based Core Networks to take advantage of scalability capabilities offered by IP-based technology

An interesting aspect brought about during latest evolutions in the field of wireless radio networks is the orientation of network management toward a service-centric / user-centric approach and the introduction of Self-Organizing Network (SON) concept [6]. This smoothens the way toward an evolution to a truly cognitive radio network which would “perceive” the local radio environment, “learn” and “act” according to the statistics of the received stimuli, “share” the knowledge among the existing transceivers and eventually create the experience of “intention” and “self-awareness”[7].

The increased granularity of radio resources to be allocated and the packet-based nature of traffic to be carried by the network allow a wireless cognitive network to be more flexible regarding the way it optimizes its operation under specific local radio conditions. Besides the variability in the offered traffic volume and QoS characteristics, there are also a large number of radio environment (indoor, outdoor; urban, suburban, rural) and deployment (macro-cell, micro-cell, and femto-cell) which could be part of the same heterogeneous network. A good approach of optimization of the radio capacity of such a wireless heterogeneous network (WHN) would be to provide means to the radio transceivers themselves to adapt to local conditions during their operation. The network would consists of software-defined radio systems having “cognition” of surrounding radio conditions and, while acting in a distributed manner, still cooperating among them to take the best decisions subject to a pre-defined constraints set agreed upon by the operator which owns the respective WHN [8].

II. PROBLEM STATEMENT

With the pioneering work of Claude Shannon regarding the mathematical theory of information, the

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wireless capacity limits have become a fundamental research area with strong impact in digital radio system design decisions and architectures. Work of Foschini and Gans [9] have predicted incentive capacity figures with some limitations regarding the asymptotic increase of the throughput versus the numbers of transmit / receive antenna elements. A. Goldsmith and all [10] have derived capacity figures for MIMO channel under the conditions of single-user, uplink (UL) multiple-user and downlink (DL) broadcast channel. In spite of the efforts done, the capacity of cellular wireless systems with multiple users / cells / antennas remains an open challenging research area.

In [11] these concepts are extended to wireless ad-hoc networks. The framework defined in [11] extends the traditional definition of Shannon capacity in order to account for delay and outage. Some loss of data is considered as acceptable as a tradeoff to higher data rates available to users. The dimensionality of such a capacity region would be of three: throughput, delay and outage[3]. These data capacity regions could be used as a benchmarking tool to test the efficiency of selected network design decisions under the QoS requirements of applications/services to be supported by respective wireless network. To derive such capacity regions an upper bound could be derived using advanced theoretical concepts, which according to [11] necessitates an interdisciplinary approach. Alternatively, improved radio system / network design would provide a lower performance bound which asymptotically would be tighter to the upper one. Such optimized network would involve with necessity a similarly optimal radio resource usage, most probable based on specific local radio conditions. Cognitive techniques applied at system and/or network level could be an important part of the solution.

The pool of radio resources has a higher dimensionality as with the previous radio technologies. By means of OFDMA-like techniques, the bi-dimensional time-frequency (T-F) area is separated into small/regular slots which allow more flexibility in radio resources allocation strategies. Each such slot (chunk) could be then optimized over the other two dimensions: power (P) and space (S). While the power level depends on power control algorithms selected, the space dimension has its roots in multiple-element antenna systems / algorithms. The selection of an optimal MIMO technique to be used with a specific user and slot depends on radio conditions encountered by respective user.

As a consequence, the radio resources optimal usage can be seen as a multi-dimensional (T-F-S-P) multi-criteria optimization problem. Based on the time-space scale of the involved fundamental phenomenon, the optimization could be done at terminal level or at network level. Of more interest here, a group of radio points (mobile users and radio access points) confined in a limited geographical area could cooperate in using the available 4-dimensional amount of radio resources. This could be called a cluster-based optimization approach.

Also, optimal usage of feedback becomes of utmost importance under the heading of cluster-based optimization methods, regarding both content and frequency of updating it.

III. RESEARCH DIRECTIONS

MIMO techniques have captured much interest because of their promising higher spectral efficiencies [12] and also their possible application with different radio technologies [13] [14]. There MIMO schemes with feedback where the transmitter has perfect knowledge of the channel state information (CSI) or channel distribution information (CDI), which outperforms the ones without feedback.

Still under realistic radio channel conditions and multi-cell deployment limitations in performances appear and difficulties in characterizing channel capacities increase. A fundamental parameter which influences MIMO performance is spatial antenna element correlation coefficient whose value depends on specific antenna geometry physical configuration and radio environment local power angular spectral (PAS) density [15].

The interference also could determine the cell-edge users (frequency reuse 1) to perform worse when specific MIMO schemes are applied. As a consequence interesting approaches of interference coordination have appeared [16] which rely on intelligent usage of OFDMA T-F resources at cell-edge and combination with Beamforming and Spatial Division Multiplexing (SDM) concepts.

The radio transmissions have a broadcast nature and cannot be confined only without the cell it is addressed to. Similarly with MIMO transmission case, the interference created could be used in a cooperative and constructive way by means of new network-MIMO techniques. It necessitates cooperation among different radio nodes with a special attention paid to feedback amount and content needed. Instead of avoiding interference, wireless capacity could be increased by a constructive usage of signals arriving from / departing towards different radio nodes.

Such cooperation-based techniques involve some difficulties implied by the amounts of feedback exchange among different radio nodes. Alcatel Lucent and Bell Labs are launching a new paradigm [17], lightRadio™, which seems to be able to offer an improved support to such cluster-based cooperative techniques. This new technology allows a set of multiple neighboring radio heads to share a common pooled baseband processing unit ("in the cloud"). As a result advanced methods for coordinating multiple radio access points become possible.

The cooperating communication approaches could be further extended over all dimensions presented

[3] A possible outage condition could be a BLER of 1% after Hybrid ARQ retransmissions

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previously (T-F-S-P) as a generic cluster-based optimization problem in order to maximize the objective function. The objective function can be subject to any optimization goal as:

- "green techniques" – minimize power consumption under the constraints of minimum QoS conditions maintaining
- maximization of spectral efficiency under the constraints of maximal power of respective radio nodes and QoS set
- or simply maximize operator's profit by increasing the amount of carried cell throughputs

A specific attention has to be paid to which problems are best suitable to be solved at network-level by means of cooperation-based techniques and those problems which can be solved (or at least ameliorated) by each radio node individually based solely on its intrinsic computational and measurement advanced capabilities. As an example, blind estimation techniques could support in having better performances without any network-level resources used [18].

As at the very ground of performances of any advanced multiple element antenna system stays the radio environment itself where the air interface acts, it becomes of utmost importance to have realistic channel and propagation models available. Realistic system level simulations should be performed in order to assess cluster-based cooperative techniques performances subject to multi-user / multi-cell interference scenarios operation.

The expectations of such realistic MIMO channel model would be:

- Wide bandwidth (up to 100 MHz) and high carrier frequency (0.5 – 6 GHz)
- Different radio environments (rural, urban, indoor…) and cell setup (macro / micro / pico…)
- Time, frequency and space selectivity / correlation characteristics modeled
- Allow different interference models (intra-, inter- cell)

Such aims were followed by an academic / manufacturer research consortium as part of the European Project WINNER (phases I / II) and the deliverables described in [19] provides a MIMO channel modeling methodology for a variety of radio environments and deployments. The delivered MIMO channel model is appealing as a consequence of its measurement-based nature and its versatility in simulating different scenarios and system topologies.

IV. SIMULATION APPROACH

The selected system-level simulation approach [22] is a drop-based one. A drop means a random distribution of mobile users over the wireless network area and each of them communicate with radio access points based on their traffic needs. To simplify the simulation, during a drop the positions of the users are not changed and their movement is only "virtually" modeled by means of impact over the fast-fading channels realizations and CQI. Realistic traffic characteristics can be applied by defining a drop duration during which a dynamic traffic simulation could be performed. Simulation time should be selected long enough to ensure convergence of simulated user performance metrics. Packets arriving into the system are not blocked (queue depths are infinite) and users traffic-specific behavior should be modeled according to traffic models implemented. The generated packets are scheduled with Proportional Fair Scheduling (or other desired scheduler as well) and individual throughput values are determined based on individual CQI & Modulation and Coding Scheme (MCS) / Link Adaptation (LA) conditions. The performance statistics are selected for mobile stations from all cells.

Other simplifications could be done as well. The network topology is determined by a regular hexagonal structure with a predefined inter-site distance and number of sectors (cells) per site. Over the area of each cell a predefined number of mobile users are randomly positioned and for each of them the channel realizations are determined.

The WINNER – Phase II (WIM2) MIMO Channel model (available on [20]) is a stochastic geometric-based channel model. A short description of the development history and available features could be found on [21].

Briefly the modeling philosophy behind WIM2 is based on the so called sum-of-sinusoids method: the sum of specular components is used to describe the variation of the channel impulse response between each transmitting and receiving antenna element. A specular component is described as a single multipath component characterized by some low-level parameters as: spatial departure and arrival angles, delay and power. These low-level parameters are generated randomly based on appropriate probability distributions. As the MIMO channels have a non-stationary evolution, the probability distributions of low-level parameters are controlled by some other parameters called Large Scale Parameters (LSPs) such as: delay spread, Angle-of-Arrival / Departure spread (AoA / AoD) , Ricean K-factor and Shadowing Spread. The LSPs have a log-normal variations and present auto- and cross-correlation properties dependent on radio propagation scenarios. The statistical distribution parameters are tabulated based on measurements campaigns and other measurement reports available in the technical literature. This modeling approach is antenna independent; it allows usage of different antenna configurations and element radiation patterns with the same channel model. Measurements results show that it is realistic to scatterers are grouped spatially into clusters (clusters number is radio scenario dependent).

Of interest for the scope of this article are the following features:

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- Radio propagation scenarios available: A1 – Indoor, A2 – Indoor-to-Outdoor, B1 – Typical Urban Microcell, B4 – Outdoor-to-Indoor Microcell, B5 – Stationary Feeder, C1 – Suburban Macrocell, C2 – Typical Urban Macrocell, C4 – Outdoor-to-Indoor Macrocell, D1 – Rural Macrocell
- Frequency range: 2 – 6 GHz
- Bandwidth range: up to 100 MHz
- Antenna Arrays: supports different geometric configurations, cross-polarization feature

A drop is represented by a channel segment with Large Scale Parameters randomly determined based on prescribed distribution functions and radio scenario and kept fixed over the duration of a drop.

As an exemplary simulation output, the generic ergodic MIMO channel capacity given by the formula (1),

$$C_n(t) = E_{H_n}\left[\log_2\left[\det\left(I_{N_R} + \frac{SNR}{N_T}\mathbf{H}_n\mathbf{H}_n^H\right)\right]\right] \quad (1)$$

is evaluated for the following setup (Table 1), under a Signal-to-Noise ratio of 10 dB.

TABLE I : SIMULATION PARAMETERS FOR MIMO CHANNEL CAPACITY EVALUATION

Radio Environment	Antenna System Physical Configuration
Urban Macrocell	1. Mobile Station (MS) – 2 Collocated xPol dipole ($\pm 45^0$) - [X] 2. Base Station (BS) – 4x2 collocated pairs xPol dipole ($\pm 45^0$) - [X X X X] - distance between BS xPol pairs d/λ =0.5

The results are pictured below in the figure 1.

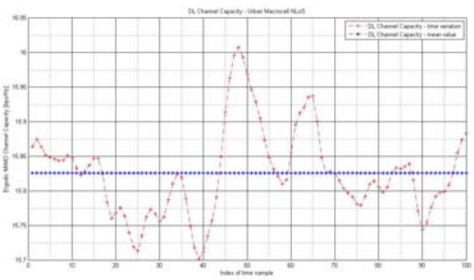

Fig. 1. DL MIMO Channel Ergodic Capacity, Urban Macrocell NLoS

V. CONCLUSIONS

A cognitive radio network has not only a "central nervous system" which strives to do the "lion's share of work", but actually consists of a large number of local replicated and distributed smart mechanisms (micro-agents) which cooperates among them and with any form of centralized intelligence of the network. Such a mechanism is oriented toward a physical phenomenon whose time-space scale determines the extension of this micro-agent.

Based on observations done in the article, a promising direction of experimental research will be on determining the impact over wireless network capacity by applying cognitive cooperative network MIMO techniques. Experimentation of "greedy" algorithms will be done by simulations, using a realistic MIMO channel models provided as deliverable of European WINNER project.

Also, cross layer harmonization relative to the allocation strategy of radio resources over the other dimensions (time, frequency, power) could be observed during simulations performed.

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