EFFICIENT WIRELESS NETWORK DEPLOYMENT BY COGNITIVE TRANSCEIVERS WITH MULTIMODAL PILOT-USE MODEMS

(Invited Paper)

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ABSTRACT

In this paper, we develop new cognitive antenna-array transceivers with a multimodal modem that, according to channel conditions, exploits the pilot signal differently yet optimally for improved adaptive channel identification and data combining. This new concept allows better throughput optimization of wireless networks while reducing the Tx pilot power at the BS. By keeping the Tx pilot power unchanged at the BS, this increased power efficiency can alternatively translate into an increased cell-size coverage, i.e., in a reduced deployment cost with relatively less BSs in a given area.

1. INTRODUCTION

One of the strongest driving forces for wireless technology evolution today is 4G (4th Generation), also known as LTE-Advanced (Long Term Evolution) or IMT-Advanced (International Mobile Telecommunications) [1], which promises to encompass two main legacy technologies among others, namely cellular and WLAN (id., IEEE 802.xx). 4G promises to deliver by 2015 high-speed wireless data transmission services at much lower costs and latencies while providing much higher rates, spectrum efficiencies and coverage. Most importantly, it promises the provision of future high-speed wireless data services everywhere closer to the mobile user in a seamless and versatile fashion, no matter what the surrounding environment and link conditions are. This stringent requirement calls for the development of new cognitive transceivers that are capable of promptly and properly self-adapting to variable operating conditions in order to constantly maximize their performance. However, it is anticipated that LTE-Advanced standard proposals, already due by the fall 2009 [2], will not include any cognitive radio flavor. Cognitive radio, still at a burgeoning stage for deployment from an industrial perspective, will rather be the focus of ”Beyond LTE-Advanced” (or 4G+) wireless technologies.

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It is precisely in this vibrant research context that we get onto the emerging cognitive radio [3],[4] from a rather uncommon perspective today. Indeed, cognitive radio is reduced in most recent works to one of its two primary objectives: exploit efficiently the radio spectrum with dynamic spectrum access (DSA) [5] that allocates the least occupied frequencies, though licensed and reserved, to secondary users who are short of bandwidth. Here we take up its second primary objective of providing highly reliable communications anywhere anytime, so far addressed in a conventional manner, but rarely tackled today from a new level of ”cognitive wireless communications” [4] where cognition could possibly handle many dynamic reconfiguration dimensions other than spectrum allocation, the conventional one. Explicitly, we aim at the development of **”cognitive antennas”** or multi-antenna transceivers which are capable of self-adjusting their antenna-array[1] processing structures and air-interface configurations for optimum performance.

One of the essential features of 4G-type radio access is the use of multiple antennas at the base station (BS) and one or more antennas at the mobile station (MS). Indeed, antenna arrays definitely stand out today as one of the most promising techniques to boost data rates and spectrum efficiencies by orders of magnitude in future wireless systems. Contributions in this very hot area are countless (e.g., [6],[7]). However, in contrast to the common bottom-up approach which often isolates the development of new antenna-array solutions in the limited application context they are usually best fitted to (e.g., either LOS or NLOS communications, i.e., either beamforming or MIMO, respectively, etc), we adopt a top-down application-driven approach where we take up one of the greatest 4G+ challenges of providing high-speed wireless access everywhere closer to the mobile user, no matter what the surrounding environment and link conditions are. This new vision calls for breaking with the current mind-set and for developing ”environment-aware” ”multi-mode” antenna-array transceivers that swiftly and optimally adapt to the vari-

[1] The multi-carrier aspect, though addressed as well in the framework of this research, will not be considered in this paper.

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able operating conditions experienced by the mobile user in terms of mobility, traffic and coverage types and propagation conditions (i.e., presence/absence of a LOS, small/large delay spreads and/or spatial correlations, etc.). This self-adjustment capability should be reflected at the level of basic functions such as synchronization and channel identification as well as in the choice of the antenna-array processing techniques (spatial diversity, multiplexing, beamforming, nulling, etc.) to be implemented at the transmitter and receiver, thereby giving birth to what we call "cognitive antennas", definitely a "notch smarter" than conventional smart or adaptive antennas. To the best of our knowledge, the development of novel antenna-array transceiver solutions from this challenging perspective of cognitive radio has not been addressed previously.

2. COGNITIVE MULTI-ANTENNA TRANSCEIVER

One of the main characteristic features of future wireless networks will be versatility with respect to the various operating conditions in which they will be expected to operate. Incidentally, pushing the limits farther in performance, coverage, etc. renders these technologies even more dependent on propagation conditions. In this context, it becomes essential that the prospective cognitive antenna-array transceivers acquire the strongest awareness of the environment changes to which they could then adapt properly so as to constantly reap maximum performance gains. As explained below, this adjustment will amount to choosing among multi-modal transceiver processing options or modes prompted mainly (among other relevant parameters) by timely and accurate estimates of the Doppler or mobile speed, the SNR, and the received pilot power (see Fig. 1). Among the principal and basic functionalities of any transceiver are channel synchronization and identification, and data modulation and demodulation (i.e., detection or combining). When powering the new cognitive antenna-array transceivers, these core modules must operate quickly, accurately and reliably in the most diverse propagation conditions while maximizing performance. In this paper, we are particularly interested in endowing the cognitive antenna-array transceivers with a multimodal modem that, according to channel conditions, exploits the pilot signal differently yet optimally for improved channel identification and data combining at i) weaker received and/or transmitted pilot power and ii) higher mobile speed, potentially translating into increased wireless network throughput, coverage and power efficiency.

2.1. Background and Concept of Multimodal Pilot-Use Modem

There are multiple ways of combining the received signals for data demodulation. Symbol detection could be coherent or non-coherent, based on maximum ratio or optimal combining (MRC/OC), incorporate centralized (i.e., parametric) or de-

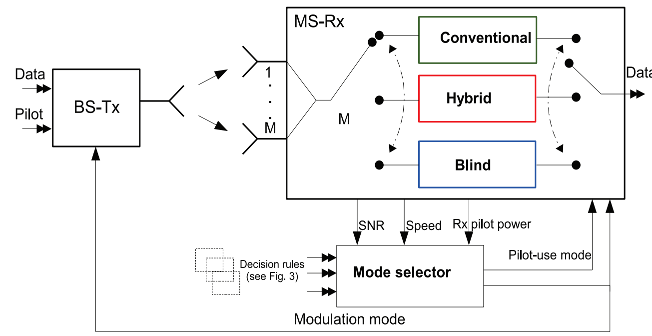

Fig. 1. Block diagram of a cognitive wireless array-transceiver with a multimodal pilot-use modem.

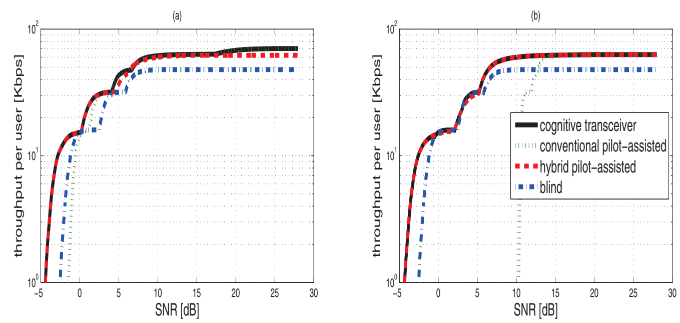

Fig. 2. Link-level throughput per user versus SNR for a Rx pilot power of (a) -10 dB and (b) -20 dB relative to Rx power of desired user at 32 Kmph.

centralized (i.e., non-parametric) interference suppression or multi-user detection, etc. In an ideal world, one would implement coherent OC without question. However, real-world channel and processing conditions render the use of other combining versions far more efficient. As one known example, fast channel variations (i.e., large Doppler spread) clearly favor blind non-coherent detection due to 1) the increased sensitivity of coherent demodulation to mounting phase estimation and compensation errors and 2) the resulting greed for more spectrum-consuming pilot overhead. Along this perspective, blind non-coherent detection techniques recently regained popularity in wireless communications [8]. However, the current mind-set is polarized such that if a pilot is available (i.e., idea of overhead accepted), then one should exploit it to estimate the channel without ambiguity and therefore implement coherent detection. If not, obviously recur to blind techniques. No common ground exists in the literature to intermingle the two concepts.

Here we break with the above conventional mind-set by recognizing that non-coherent detection (i.e., blind mode), in some situations (e.g., mobile is far from the BS and/or has high speed), can perform best despite the presence of a ref-

Parameter	Value	Comment
BW	5 MHz	channel bandwidth
f_c	1.9 GHz	carrier frequency
R_s	16 (80%)-128 (20%) KBaud	basic Baud rate
L	256 (80%)-32 (20%)	spreading factor
r_c	1/2	convolutional coding rate
T_f	5 ms	frame duration
f_{PC}	1600 Hz	PC update frequency
ΔP_{PC}	±0.25 dB	PC adjustment
τ_{PC}	0.625 ms	PC feedback delay
BER_{PC}	10%	simulated PC feedback BER
$\text{PC}_{\min}^{\max}$	±30 dB	PC margin
M	2	number of Rx antennas
P	3	number of paths
$\bar{\varepsilon}_p^2$	(0, 0, 0) dB	multipath power profile
e	4	path-loss exponent
σ_s	6 dB	std of log-Normal shadowing
P_{Tx}^{π}	36/26/16/6 dBm	Tx pilot power
P_{Rx}^{δ}	-98 dBm	Rx power by desired user

Table 1. Parameters used in the link- and system-level simulations.

erence signal[2] and that pilots, used differently in two less extreme modes, allow more efficient quasi-blind coherent or coherent detection, respectively [10]. In the coherent mode (i.e., conventional), the pilot is used directly for conventional channel identification. In the quasi-blind coherent case (i.e., hybrid mode), a pilot received with a relatively much lower power (either intentionally reduced at the BS for increased power efficiency or intentionally detected relatively farther from the BS for increased coverage) is used to estimate and compensate the phase ambiguity of a blindly identified channel by long-term averaging of the combiner's soft output.

A preliminary link-level study conducted previously [9] to explore, to the best of our knowledge for the first and only time since, the multimodal pilot-use concept [3] - which finds today best opportunity for investigation within the upcoming initiatives on Beyond LTE-Advanced, has shown over a circuit-switched CDMA downlink that, in order, 1) the blind, 2) the quasi-blind coherent, then 3) the coherent mode surpass the two others, one at a time, with the received pilot power relatively increasing. Here, we push what was then an embryonic concept to its full extent by i) integrating all three modes in a working multimodal modem implementation for cognitive antenna-array transceivers (cf. below), ii) combining the multi-modal pilot-use concept with the adaptive modulation scheme (integration of adaptive modulation and coding, though possible, was not addressed in this work), and iii) recognizing that the Doppler spread (or mobile speed), the SNR, and the pilot power, all together and not the pilot power alone (i.e., **increased environment awareness**), are the appropriate parameters needed to decide the mode selection.

[2] Yet still useful for other mobiles experiencing other channel conditions.

[3] Put on hold only due to lack of perspectives at the time, after 3G standardization.

2.2. Implementation of Multimodal Pilot-Use Modem

For implementation, we select the STAR receiver developed for wideband CDMA and beyond [9],[10] and assess it on the downlink. This receiver already integrates the three modem modes described above in a unique adaptive channel identification procedure and hence offers a simplified structure. The block diagram of the proposed cognitive transceiver in Fig. 1 shows for simplicity three different modems. With STAR, most of the modem components are actually identical and hence only a few feedback/input components differ from one modem version to another, hence rendering hardware implementation much easier. All mathematical and algorithmic details of each mode can be found in [10]. Besides, this receiver supports various upgrades that allow operation over multi-modulation [11] and multi-carrier [12] air-interfaces among other things. For convenience, the single-carrier CDMA air-interface was chosen here to validate the new multimodal concept in a timely manner, yet the concept itself remains valid with *a priori* any multi-carrier air-interface. The conventional and hybrid modems of STAR implemented in this work support the BPSK, QPSK, 8PSK, 16QAM and 64QAM modulations while the blind version operates with DBPSK, DQPSK, and D8PSK only (i.e., differential). Each modem is integrated in a full link-level transceiver that includes a convolutional codec, an interleaver and a deinterleaver, a closed loop for power control (PC) of data, etc. The pilot signal is code multiplexed without PC. Time synchronization, supported by STAR [11],[12], was set perfect here to speed up the link-level simulations. All link-level parameters are given in Tab. 1.

In a learning phase, the cognitive transceiver is operated with each mode (pilot use and modulation) separately to measure the resulting FER versus SNR at different values of the mobile speed and Rx pilot power (both covering their entire practical range for a given environment). The resulting link-level FER versus SNR curves are then translated into link-level throughput per user versus SNR curves (cf. examples in Fig. 2) to allow identification of the best modem mode that maximizes throughput versus SNR, speed and received pilot power, as illustrated in Fig. 3. The latter shows that as the Rx pilot power decreases, the hybrid then the blind versions stand out as the best modes, more so at higher speed.

In an operating phase, the cognitive transceiver measures the SNR, the Doppler speed (or mobile speed), and the Rx

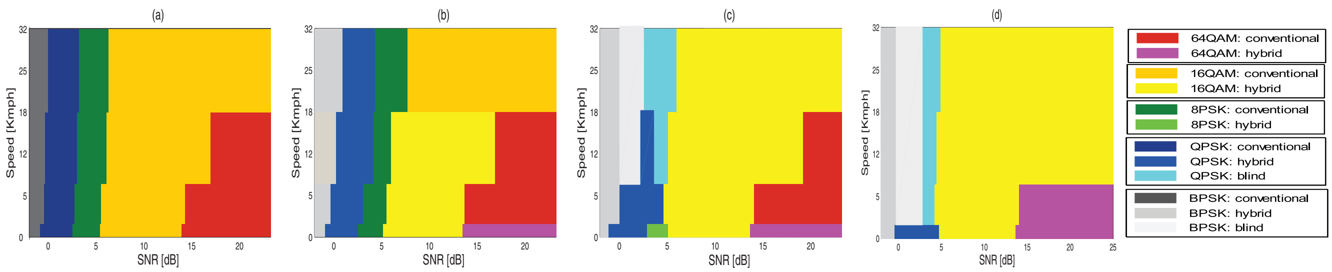

Fig. 3. Decision rules for best mode selection (i.e., modulation and pilot use) w.r.t. SNR, speed and a Rx pilot power of (a) 0 dB, (b) -10 dB, (c) -20 dB, and (d) -30 dB relative to the Rx power of the desired user.

pilot power, then feed them to a mode selector which in turn, according to channel conditions, instructs both the BS-Tx and MS-Rx to change the modulation type (DBPSK, BPSK, DQPSK, QPSK, D8PSK, 8PSK, 16QAM or 64QAM) and the MS-Rx to change the pilot-use type.

3. SYSTEM-LEVEL PERFORMANCE ANALYSIS & PERSPECTIVES

3.1. System-Level Simulation Set-Up and Approach

We use a system-level simulation tool on the downlink of a wideband CDMA network that uniformly populates in each snapshot a square grid of $N_C = 11 \times 11 = 121$ square cells with $N_C \times C$ mobile users where C denotes the average number of users per cell or cell capacity. In this paper, we consider a macro-cell environment [13] for different cell sizes. We assume that 80% of the total users require a service with a basic (i.e., with BPSK modulation) Baud rate of 16 Kbaud and 20% require a basic Baud rate of 128 Kbaud. Other system-level parameters are listed in Tab. 1. The tool runs 5000 snapshots.

At each snapshot, the simulation tool first computes the SIR measured at the MS of the desired user as follows:

$$SIR = \frac{L P_{Rx}^{\delta}}{P_{Rx}^{\delta} \sum_{k=0}^{N_C-1} \sum_{\substack{i=1 \\ (i,k) \neq (d,0)}}^{C_k} \frac{r_{k,i}^{\alpha}}{10^{\frac{\xi_{k,i}}{10}}} \frac{10^{\frac{\xi_{k,d}}{10}}}{r_{k,d}^{\alpha}} + P_{Tx}^{\pi} \sum_{k=0}^{N_C-1} \left(\frac{r_0}{r_{k,d}}\right)^{\alpha} 10^{\frac{\xi_{k,d}}{10}}},$$

s.t. $\sum_{k=0}^{N_C-1} C_k = N_C \times C$ where $10^{\frac{\xi_{k,i}}{10}}$ and $10^{\frac{\xi_{k,d}}{10}}$ are the log-Normal shadowing factors between the BS k and the interfering mobile i and the desired mobile d (served by BS 0 without lack of generality), respectively, $\xi_{k,i}$ and $\xi_{k,d}$ are centered Gaussian random variables with variance σ_s^2; $r_{k,i}$ and $r_{k,d}$ are distances between the BS k and mobiles i and d, respectively, and $r_0 = 2\frac{\Delta^2}{\lambda}$ is the reference distance fixed to 0.1 m where Δ is the antenna dimension and λ is the wavelength. It also measures the pilot power received at the desired MS d relative to its own data power. If the Tx exceeds the available BS power of 40 Watt, the mobile is denied access. Due to lack of space we do not show the figures of blocking probability. In a second step, the tool translates each transceiver performance from the link- to the system-level by mapping the measured SIR value as an entry of the appropriate link-level curve of user throughput versus SNR at the measured Rx pilot power for a given mobile speed (cf. examples in Fig. 2) and for one of the processing gains $L = 32$ or $L = 256$ depending on the basic Baud rate required by the user of interest. In a third and final step, it gathers from all the snapshot values a CDF for the user throughput and provides useful throughput statistics such as the average throughput per user or the average total throughput (i.e., the former multiplied by the average cell capacity), the performance metric considered for assessment in this work.

3.2. Simulation Results: Analysis and Perspectives

Fig. 4 shows the average total throughput curves which are obtained for the four Tx pilot powers values selected in Tab. 1 for different cell sizes. These curves suggest the following:

• For a Tx pilot power of 36 dBm, the typical ratio of about 10% of today's 40 Watt BS power, the system shows poor performance. This is due to the inteference caused by the pilot signal which increases when the cell size decreases. To compare the performance of the different modems, we consider without loss of generality the average of the system performance for a capacity between 20 and 100 users. The conventional mode offers an average of about 864 Kb/s for a cell size of 500×500 m^2 and Tx pilot power equal to 26 dBm in Fig. 4.1.b. The same performace is reached by the cognitive transceiver for a cell size of 550×550 m^2 and a Tx pilot power of 16 dBm, thereby offering a reduction in the number of BSs required to cover the same area by 20% and in the pilot power by factor of 10 as shown in Fig. 4.2.c. Now comparing Fig. 4.1.b and Fig. 4.3.b, as much as 45% less BSs are required by the cognitive transceiver for a cell size of 600×600 m^2 with only 6% throughtput loss (with respect to the conventional mode in Fig. 4.1.b.

• Overall, the new concept of a multimodal pilot-use modem for cognitive transceivers allows better throughput optimization of wireless networks while reducing the Tx pilot power at the BS. By keeping the Tx pilot power unchanged at the BS, this increased power efficiency can alternatively translate into an increased cell-size coverage, i.e., in a reduced de-

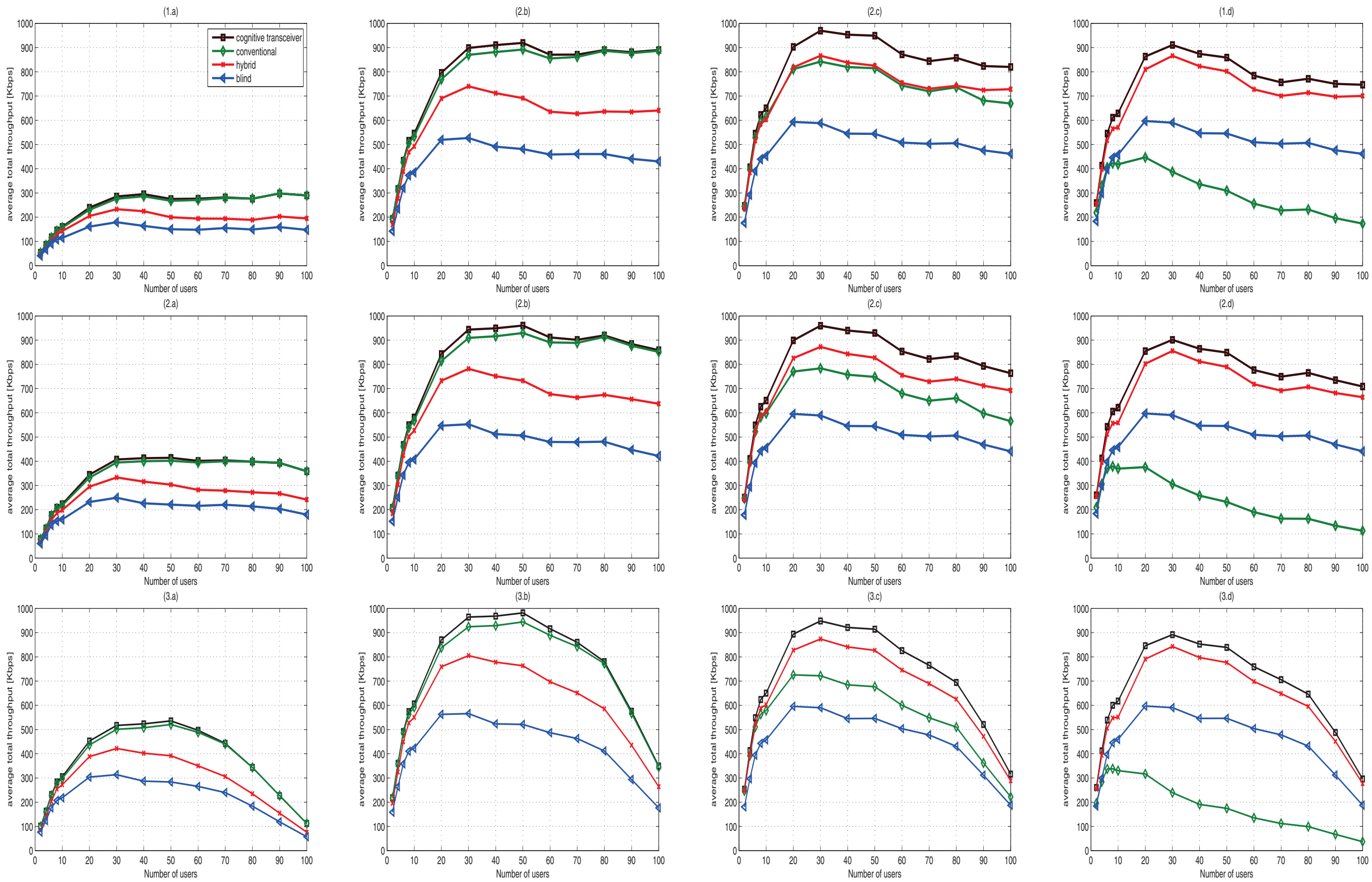

Fig. 4. System-level average total throughput versus the number of users for a cell size [m^2] of (1) 500×500, (2) 550×550 and (3) 600×600 and for a Tx pilot power [dBm] of (a) 36, (b) 26, (c) 16 and (d) 6, and for a speed [Kmph] of 2 (50%), 32 (30%) and 128 (20%).

ployment cost with relatively less BSs over a given area. It is also timely in the new context of the growingly popular "green IT" initiatives where even if the individual savings per BS would be in the range of a couple of Watts, the aggregate power savings over multiple wireless networks could be significant.

• Ongoing efforts in the framework of this work currently assess the cognitive transceiver performance gains in other types of environments (micro-cell, suburban, rural). It also tackles the issue of environment-specific Tx pilot power optimization at the BS and develops an efficient protocol for live modem handoff among the pilot-use modes.

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