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Performance of an Adaptive Space-Time Processing Receiver for the User Terminal of 3G WCDMA Systems under COST-259 Channel Models

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Abstract— **This paper presents an adaptive multi-target space-time architecture for downlink receivers in the user terminal of WCDMA systems under soft handoff. The receiver consists of M antennas and K array processors, each one followed by a chip-rate equalizer and a despreader. The resulting signals from these K branches are combined in an adaptive ratio combiner which is updated by the common channel information in UTRA FDD systems. When a large number of antennas is used each array processor is able to collect a given target ray and filter out all the others. On the other hand, when only a small number of antennas is used, due to cost or physical limitation, the chip-rate equalizers try to eliminate the residual interchip interference that strongly affects receiver performance. In both cases an efficient coherent receiver is obtained that exploits the space and time diversity in the incoming signal at the user terminal. All the signal structure of the FDD WCDMA downlink signal is exploited for improved performance. Simulation results using COST-259 channel models for vehicle speed of 50 km/h are compared with results obtained for a difficult hypothetical fixed channel condition.**

I. INTRODUCTION

Third Generation (3G) cellular systems will provide ubiquitous high-speed wireless Internet services to the user terminal, either for fixed, portable or mobile applications [1][2]. Vehicular devices, wireless home appliances and hand-held devices, such as advanced cellular phones and PDAs with Internet access, are typical examples of next generation consumer electronics for wireless multimedia. Wideband Code Division Multiple Access (WCDMA) system is the emergent technology that will provide the advanced cellular infrastructure for these large-scale applications [1][3]. Since data traffic in the downlink direction is expected to be much larger than in the uplink channel for these systems, efficient receivers in the user terminal are required to guarantee the necessary quality-of-service for multimedia applications.

Multi-user interference in base station receivers is the main source of degradation in the uplink channel. On the other hand, in downlink receivers under soft handoff the loss of code orthogonality due to multipath propagation is the main source of problems in user terminal performance. The use of multiple antennas in downlink receivers greatly improve their ability to recover code orthogonality, specially for fast time-varying channels or for bad urban area environments with strong multipath propagation. Multiple antennas in cellular base stations is already a practical reality for GSM and TDMA systems [4]. Downlink receivers for smart antennas in mobile stations has been studied in [5][6][7], and others.

The present paper describes and analizes an efficient space-time architecture for receivers with multiple antennas in the user terminal of 3G WCDMA systems. A multi-target architecture [3] is used in such a way as to transform a large optimization problem into a number of much smaller convex sub-problems. The corresponding algorithms are fully adaptive and do not require the knowledge of the downlink channel characteristics, except for the path delays that can be easily estimated from the unmodulated common *pilot* channel (CPICH). A robust receiver is then obtained which is suitable for fixed or time-varying channels in bad urban areas.

The present space-time architecture consists of M antennas and K array (or spatial) processors, each one followed by a chip-rate equalizer and a despreader. The resulting signals are then combined in an adaptive ratio combiner which is updated by the unmodulated common channel information (CPICH in UTRA FDD sys-tem). When a large number of antennas is used and all incoming rays are spatially separated, there is no need for the chip-rate equalizers, since each array processor is able to collect a given target ray and filter out all the others. On the other hand, when only a small number of antennas is used (due to cost or physical limitation), the presence of the chip-rate equalizers are extremely important, since they eliminate any residual interchip interference that strongly affects receiver performance. In both cases an efficient coherent receiver is obtained that exploits the space and time diversity in the incoming signal at the user terminal. All the signal structure of the FDD WCDMA downlink signal is exploited for improved per-formance.

II. SMART ANTENNAS

Smart antenna arrays is a technique of combining the signals from (or to) an array of small-gain antennas to alleviate the effect of fading, multipath, noise, interference, etc, [10][11][12]. Usually, a wireless channel has a non-ideal behavior. In many cases of real wireless channel, there is obstruction of the direct ray, so the receiving antenna sees only the reflected rays. In this

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kind of channel, the envelope and phase of the received signal vary when the transmitter or the receiver is moving. The damaging effects of fading may be particularly important in the moments of deep fading, i.e., the instants when the signal amplitude decreases dramatically. An array of antennas can use spatial diversity to minimize the effect of deep fading, exploiting the fact that when the signal from one direction (or from one antenna) is suffering from a dip, the signal from another direction (or from another antenna) may be not.

Depending on the chosen implementation, a beamforming antenna array with *a fairly large number of elements and space-time processing in a downlink receiver* is able to:

- create strong lobes in the direction of the desired signals and, simultaneously, deep nulls in the directions of undesirable interferences;
- collect spatially separated rays to provide diversity gains;
- significantly improve the transient and steady-state performance of chip-rate equalizers;
- decouple the receiver optimization problem into a number of simpler problems (usually convex sub-problems with global optima);
- dispense with the need of Direction of Arrival (DOA) estimation;
- incorporate imperfect antenna callibration and mutual coupling effects into the array processor;
- significantly improve receiver performance in fast time-varying channels;
- provide useful feedback information to base stations to improve downlink beamforming.

These are an impressive collection of benefits that will certainly improve the performance of advanced wideband 3G wireless systems. However, for applications in small handsets there is a severe space limitation that precludes the use of a fairly large number of sensors. Fortunately, it is reasonable to accept that these handsets will not demand a very high bit rate in normal operation. On the other hand, new concepts of *wearable portable devices* may solve this space limitation problem, and a large number of sensors may become a reality for this application. On the other hand, for fixed home appliances, large portable devices, vehicle applications, and others, space limitation is not an obstruction for using a large number of antennas.

III. WIDEBAND CDMA

Wideband Code-Division Multiple Access (WCDMA) is the technology developed for the FDD mode of the European third-generation mobile communication standard - UMTS (Universal Mobile Telecommunication System). This technology is based on the direct sequence CDMA (DS-CDMA) principle, which means that all users share the same carrier through orthogonal spreading codes. In fact, WCDMA uses orthogonal codes with variable spreading factors to provide different multirate services (up to 2 Mb/s). The information is spread over approximately 5 MHz bandwidth with a 1.8 GHz carrier. Other systems, like CDMA2000, also employ the same principle of wideband spreading, and have similar objectives in providing high-speed Internet services to mobile receivers.

Unlike the second generation DS-CDMA system (IS-95), the FDD WCDMA intercell operation is asynchronous, with no base-station dependence on external timing source, like the global positioning system (GPS). Other differences are the use of coherent detection in both forward and reverse links of WCDMA, which increases the link capacity, and the use of fast transmit power control (TPC) based on signal-to-interference ratio to increase coverage. WCDMA systems also support the use of advanced techniques such as adaptive antenna arrays and equalization. This is possible because of pilot bits included in the data structure of the physical channels. Pilot bits are also used for coherent reception, power control signaling and rate information for rate detection, but may also be used for adaptive antenna arrays and equalization.

In the physical layers, the WCDMA system employs a frame structure [13]. Each frame lasts 10ms and consists of 15 slots. The chip rate is 3.84Mcps which corresponds to 2560 chips per slot. The data rate is dependent on the spreading factor, which varies in the power of 2 from 256 to 4 in the uplink and from 512 to 4 in the downlink. For example, if the channel uses a spreading factor of 16, then the bit rate is 480 Kbps (3.84Mbps/16×2). Therefore, the bit rate varies from 30 Kbps to 1920 Kbps for uplink and from 15 Kbps to 1920 Kbps for downlink. The modulation scheme is QPSK and the system supports three types of channel coding: convolutional coding, turbo coding or no channel coding.

IV. COST-259

COST (COperation europeénne dans le domaine de la recherche Scientifique et Technique) is a European Union forum for cooperative scientific research. Within the COST action 259 (COST-259), a general structure of a directional channel model was developed [14]. This model generality allows the use of COST-259 for many different types of studies, such as system simulation and network planning. For example, COST-259 models are very well suitable to investigate the impact of adaptive antenna arrays in 3G UMTS performance, but it is also useful to analyze link capacity and coverage for 2G systems such as GSM and IS-95. In fact, its application is valid at least in the range from 450MHz to 5GHz. COST-259 directional channel models fulfill the following properties:

- Directional in both base and mobile stations;
- Wideband;
- Fast and slow fading, channel variations due to non-stationary scenarios and dynamic evolution of paths;
- Polarization;
- For narrowband or non-directional purposes, it should be comparable or better than the existing models.

The model is based on the concept of clusters and the number of clusters in a model depends on the adopted scenario. A cluster is defined as a set of multipath components which experiences the same large-scale behavior [14], i.e., a drift in its parameters. Each cluster will have its own parameters, such as delay spread and angle spread. Consequently, it is also necessary to define the spreading of the clusters. The large-scale behaviors are independent for components of different clusters. A cluster can arise, for example, either due to a large cross section of a high building in a macrocell typical urban scenario, or due to an open door in an indoor picocell scenario. COST-259 defines three classes of scenarios: macrocell, microcell and picocell. This classification is just the higher level division for the scenarios, which are sets of parameters defined in COST-259 to represent the different possible radio channel behaviors.

V. THE ADAPTIVE SPACE-TIME DOWNLINK RECEIVER

The basic macro-diagram for the WCDMA baseband equivalent model for the proposed receiver is presented in Figure 1. It consists of a bank of M antennas and K linear array processors followed by chip-rate equalizers, despreaders and descramblers, and a weighted signal combiner. All these sub-systems are adaptively updated according to the useful information imbedded in the WCDMA signals from all the relevant base stations. If soft-handoff is used, the corresponding signals are automatically collected in the weighted signal combiner in order to provide spatial diversity and soft-handoff capability. The interfering users' spreading codes are not really required for optimum performance, but we assume that the aggregation of dedicated pilot symbols in each slot from all the base stations are known. This is an important feature for fast convergence of the adaptive algorithms in the K linear array processors and in the chip-rate equalizers, and needs to be better investigated. On the other hand, the adaptation of the weights in the signal combiner does not depend on this assumption.

We assume that the downlink WCDMA signal is synchronous at the base station. Note that this receiver is inspired by the multi-target receivers used in uplink channels for multi-user detection at base stations [3]. However, due to the synchronous nature of downlink signals and the larger angle spread at the user terminal, some peculiar differences apply to the present approach. One of these is the need for the chip-rate equalizers, which may be required in the situations when a given array processor does not have enough resolution to isolate the desired incoming ray (target ray). In this case the signal after the array processor may consist of multiple echoes of the desired signal, which can hopefully be taken care of by the chip-rate equalizer. Also, the present approach uses an efficient "adaptive ratio combiner" that is guided by the known information in the UTRA-FDD continuous common channel. Notice that the usual maximal ratio combining technique would require the knowledge of all the channel complex coefficients.

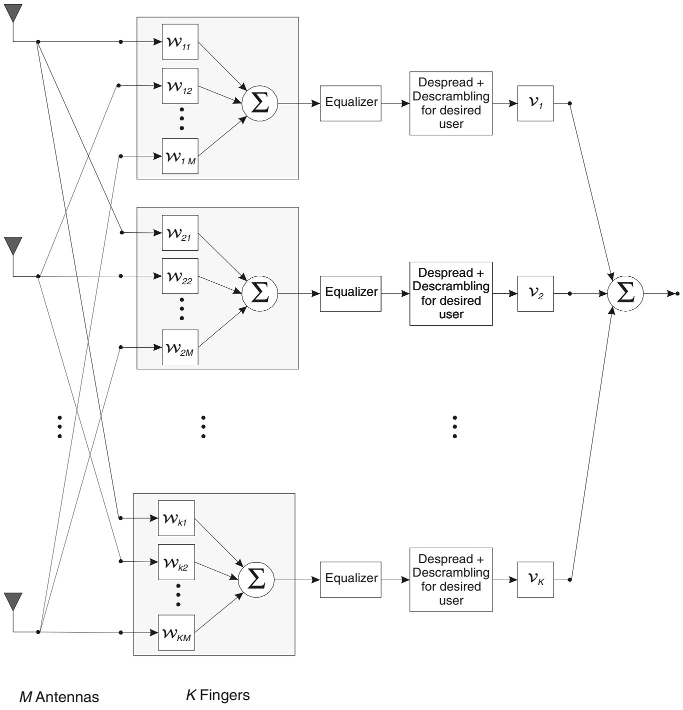

Fig. 1. Basic configuration of the downlink receiver.

Path		Azimuth	Coefficient	Delay (in chips)
BS 0	(0,0)	60^{o}	1	1
	(0,1)	0^{o}	0.5	2
BS 1	(1,0)	120^{o}	1	4
	(1,1)	150^{o}	0.4	5
BS 2	(2,0)	270^{o}	1	8
	(2,1)	330^{o}	0.3	9

Fig. 2. Time-invariant channel used in the simulations.

VI. SIMULATION RESULTS

Simulation results for the proposed Multi-Target Space-Time Receiver (MT-STR) were obtained using a simulation tool developed with MatLab Simulink for FDD WCDMA. Three propagation scenarios were used. The first one is a difficult hypothetical fixed channel condition, in which 3 equally spaced base stations (BS) cooperate in a soft handoff scheme. The channel profile for this time-invariant scenario is depicted in Figure 2. The second scenario is similar to the first one, but now we use a COST-259 channel model for typical urban area, macro cell environment and vehicle speed of 50 km/h. The delay spread in the channel model was set to 16 chips. In the third scenario we are interested in the receiver performance when only two antennas are used. In this case we have considered only one base station transmitting in a multipath environment identical to the second scenario, i.e., using COST-259.

The algorithms were tested for two different situations. In the first case we have considered the user terminal under soft-handoff with the MT-STR using 6 antennas. In the second case we have considered only one base station and the MT-STR with only two antennas. The spreading factor was set to 16, and all the user's signals were transmitted with the same power for both cases. The algorithms were tested with different numbers of interferers per cell and for different numbers of adaptive array processors (fingers).

From the simulation results we obtain the BER curves as a function of E_b/N_0 for the desired user. We must emphasize, however, that the values of E_b/N_0 *were determined at each antenna element*, as is normally assumed in the literature.

A. Scenario 1

The following results use the LMS algorithm and compare the BER graphs as a function of E_b/N_0 for 6 fingers and for 6 antennas. Results for a 1-finger receiver and for a Rake receiver with only one antenna are also presented for comparison. The results for 6 antennas are presented in Figure 3. The gains obtained with the use of antenna arrays in the user terminal are quite clear from these results. At least for this (static) channel condition, the performance of the space-time receiver with 6 fingers *is practically limited by additive Gaussian noise and not by interference*. This means that code orthogonality was completely recovered in the receiver, even under this soft-handoff operation.

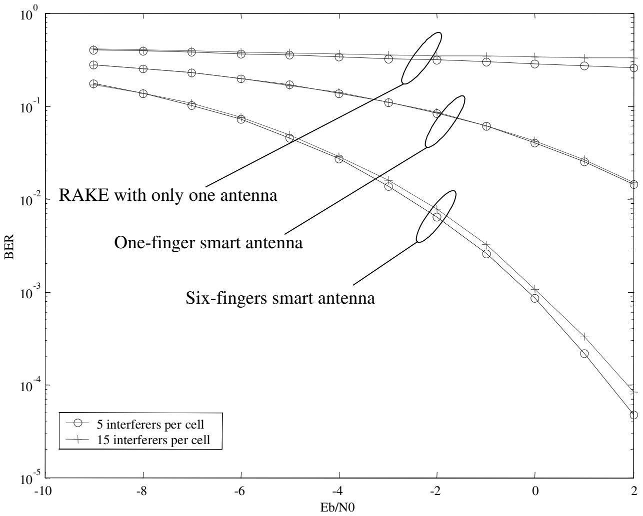

Fig. 3. BER as a function of E_b/N_0 for 6 antennas and 6 fingers. Results for a one-finger receiver, as well as for Rake receiver with only one antenna, are also shown.

B. Scenario 2

The case of time-variant channel was simulated using COST-259 channel models. We assume that the mobile user terminal is moving at 50 km/h in the border of three cells. Each cell has 5 or 15 other users, meaning that the desired signal has 15 or 45 interferers, respectively.

The delay spread for the multipath components was set to 16 chips, and the apreading factor was set to $SF = 16$, as mentioned before. Since we are interested in channel models for urban environments, the angle spread in the user terminal is 360 degrees, which means that the receiver is operating under scattering surroundings.

The results presented in Figure 4 compare the BER graphs as a function of E_b/N_0 for 6 antennas and 6 fingers, with two fingers locked to each BS. Results for the proposed receiver without the DFE's and for the RAKE receiver are also presented for comparison. The gains obtained with the use of only spatial processors, that is, with the MT-STR without equalizers in the user terminal, is evident when compared with the RAKE receiver. However, the performance of the MT-STR now degrades when the number of interferers in a cell increases. This is due to the fact that the code orthogonality was not fully recovered, since the MT-STR technique is now non-ideal (the number of rays is much larger than the number of antennas) and the channel is time-varying. The use of Decision Feedback Equalizers following the array processors is then well justified to recover this loss in performance, and this is shown in the graphs corresponding to MT-STR-DFE. As one can see from these results, the gains obtained with the use of DFE's is quite significant. All DFE's were implemented with 32 forward taps and 16 backward taps.

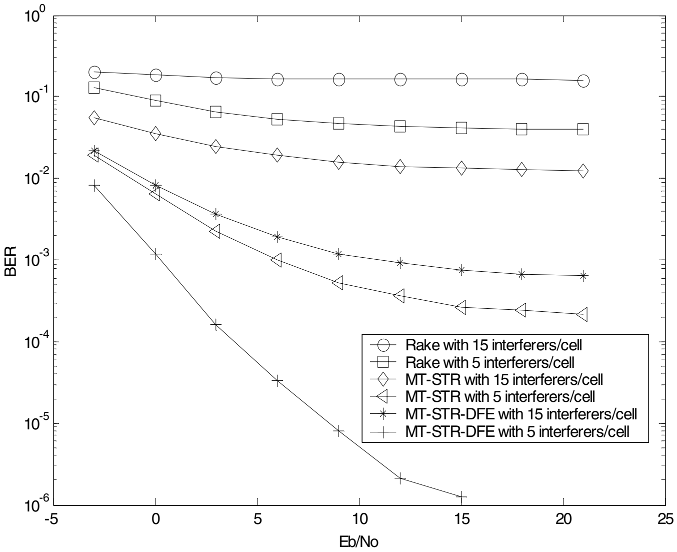

Fig. 4. BER as a function of E_b/N_0 for three types of receivers: RAKE receiver, the proposed receiver without equalization (MT-STR) and with equalization (MT-STR-DFE). The adopted structures use 6 antennas, 6 adaptive spatial processors (arrays), 32 forward and 16 backward taps for the DFE.

C. Scenario 3

For this scenario we have used a non-ideal delay estimation based on the Maximum Likelihood criterion, as discussed in [8]. In the 3GPP WCDMA system this operation can be implemented, for example, through the primary or secondary CPICH channels.

Simulations for the RAKE receiver with one antenna and 4 fingers, either with ideal and non-ideal channel estimation, are presented. Simulations are also presented for the MT-STR with 2 antennas (for $\lambda/2$ spacing) and 4 spatial combiners, using the delay estimator discussed above and the Decision Feedback Equalizers. In this case, the 4 strongest taps from the 2 antennas were selected as targets for the 4 adaptive spatial combiners. In Figures 5 and 6 we show the Bit Error Rate as a function of E_b/N_0 (measured in each antenna), for 7 and 13 users in a cell, respectively. Notice from the graphs that for the RAKE receiver there

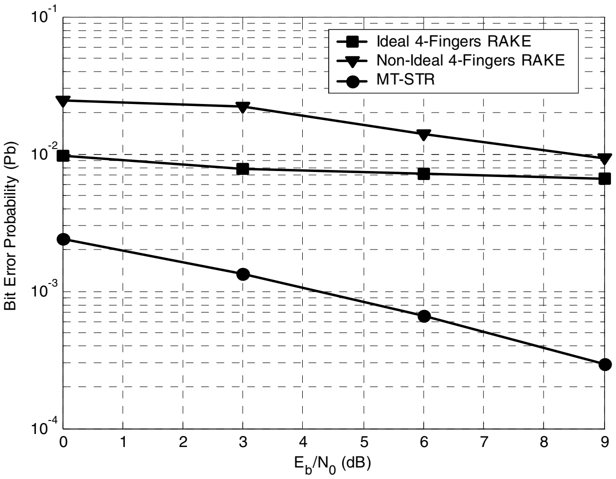

Fig. 5. Bit Error Rate as a function of E_b/N_0 for 7 users in a cell.

is a visible loss in performance when non-ideal channel estimation is used. It is also clear that the use of two antennas in the MT-STR receiver provides a significant improvement in performance, even when non-ideal delay estimation is used.

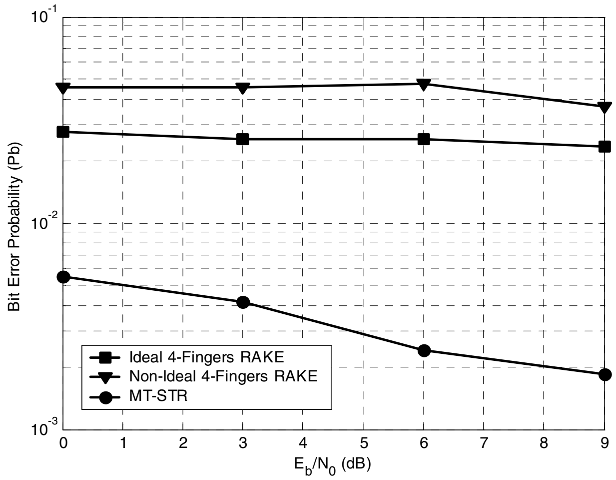

Fig. 6. Bit Error Rate as a function of E_b/N_0 for 13 users in a cell.

VII. CONCLUSIONS

The present results show that advanced receivers with multiple antennas at the user terminal are very effective in combating mutipath interference in WCDMA systems. In fact, these receivers can take advantage of multiple propagation rays, specially for large angle spreads which are typical of urban area environments. In particular, antenna arrays with chip rate equalization are most effective in multipath channels when low values of spreading factors are used. For example, in 3G evolution systems for high-speed downlink tranmission, such as the High Speed Downlink Packet Access (HSDPA) standard, efficient downlink receivers with multiple antennas may provide the necessary performance required for the highest bit rates attainable with 3G WCDMA technology.

Equalization in the MT-STR receiver is particularly important for hand-held devices with a small number of antennas. However, for home appliances and vehicle applications a larger number of antennas can be used, resulting in better receiver performance. Moreover, since the present MT-STR receiver works with decoupled algorithms, it may prove quite effective for time-varying channels in mobile applications.

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