A High Capacity CDMA Array-Receiver Requiring Reduced Pilot Power*

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Abstract— **Use of coherent modulation for the uplink of wireless CDMA systems requires pilot signals which contribute to the interference seen by other users. In previous work we showed that blind array-receivers outperform pilot-channel assisted array-receivers in capacity for various operating conditions. These array-receivers avoid additional interference due to pilot signals and achieve better channel identification using relatively stronger data signals. However, for BPSK signals they identify the channel within a sign ambiguity and require differential modulation and decoding of coherently detected bits. In this contribution we implement coherent modulation and detection and further increase the advantage of this blind channel identification scheme by introducing a new pilot called "pilot-sign". This pilot simply allows resolution of the channel sign ambiguity after its estimation by long-term averaging of the pilot-channel combiner output. Analysis indicates that the resulting pilot-sign assisted array-receiver requires very weak pilot power ratios, in the range of a fraction of a percent, and allows very significant pilot power savings and large capacity gains compared to pilot-channel array-receivers.**

I. Introduction

To increase the uplink capacity of wideband wireless CDMA networks [1], future standards are expected to implement coherent detection with a pilot. This pilot should allow the identification of the channel, particularly the estimation of its phase offset. The performance of pilot-assisted systems in Rayleigh fading channels has been widely studied [2]-[6]. The effects of channel estimation errors on performance [3]-[5] are of particular interest in pilot-assisted schemes. Their knowledge allows optimization of performance [2],[4]-[6] and the allocation of an optimal pilot-to-data power ratio [4]-[6].

We have previously reported on the analysis and evaluation of pilot-assisted CDMA array-receivers adaptive to Rayleigh fading [7]. The case of a blind array-receiver STAR [8] was also included for comparative evaluation. The analysis showed that blind array-receivers may perform better than pilot-assisted versions at higher fading rates and qualities of service. The blind version studied, which does not need a pilot, requires differential modulation and decoding. In this contribution, we consider coherent demodulation in the blind version using a very weak pilot called "pilot-sign". Our objective is to determine the pilot-to-data power ratio leading to highest capacity.

* Work supported by the Bell/Nortel/NSERC Industrial Research Chair in Personal Communications.

II. Formulation and Background

We denote by M the number of the uplink receiving antennas at the base-station and consider a multipath Rayleigh fading environment with number of paths P and Doppler frequency f_D. The data is BPSK modulated at the rate $1/T_s$ where T_s is the symbol duration. We assume that each user's signal is spread with a processing gain L using two different spreading codes, pilot+data, possibly orthogonal. The pilot signal, spread with only the pilot code, is multiplexed with the data.

After despreading of the data channel, we obtain the post-correlation model (PCM) of the received signals over the $M \times P$ spatio-temporal diversity branches in the data observation vector [7]:

$$\underline{Z}_n^\delta = \underline{H}_n s_n^\delta + \underline{N}_n^\delta = \underline{H}_n \psi_n b_n + \underline{N}_n^\delta \,, \tag{1}$$

where $s_n^\delta = \psi_n b_n$ is the data signal component, b_n is the BPSK data sequence and ψ_n^2 is the total received power. $\underline{H}_n$ is the $M \times P$ spatio-temporal Rayleigh fading channel vector normalized to $\sqrt{M}$. $\underline{N}_n^\delta$ is a spatially-uncorrelated Gaussian interference vector with mean zero and variance σ_N^2 after despreading of the data channel. The resulting input SNR after despreading is $SNR_{\text{in}} = \psi^2/\sigma_N^2$ per antenna element.

Using the above PCM model for the pilot channel after despreading, we obtain the following pilot observation vector [7],[8]:

$$\underline{Z}_n^\pi = \underline{H}_n s_n^\pi + \underline{N}_n^\pi = \underline{H}_n \xi \psi_n + \underline{N}_n^\pi \,, \tag{2}$$

where ξ^2 denotes the allocated pilot-to-data power ratio and $\underline{N}_n^\pi$ is a zero-mean spatially-uncorrelated Gaussian interference vector with the same variance as $\underline{N}_n^\delta$ (*i.e.*, σ_N^2).

III. Pilot-Sign Assisted STAR

Using the channel estimate $\hat{\underline{H}}_n$ at iteration n, STAR first performs a simple extraction of the data signal component by spatio-temporal maximum ratio-combining (MRC) [7],[8]:

$$\hat{s}_n^\delta = \text{Re}\left\{\frac{\hat{\underline{H}}_n^H \underline{Z}_n^\delta}{M}\right\} . \tag{3}$$

In the presence of a pilot, STAR could also extract the pilot signal component by the same MRC rule:

$$\hat{s}_n^\pi = \text{Re}\left\{\frac{\hat{\underline{H}}_n^H \underline{Z}_n^\pi}{M}\right\} . \tag{4}$$

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The data sequence b_n is then estimated as:

$$\hat{b}_n = \text{Sign}\left\{\hat{s}_n^\delta\right\} \ . \quad (5)$$

The total received power ψ_n^2 is estimated by the following steps[1]:

$$\hat{\psi}_n^2 = (1-\alpha)\hat{\psi}_{n-1}^2 + \frac{\alpha}{1+\xi^2}\max\left\{|\hat{s}_n^\delta|^2 + |\hat{s}_n^\pi|^2 - \hat{\sigma}_{\text{res}}^2, 0\right\}, \quad (6)$$

$$\hat{\sigma}_{\text{res}}^2 = (1-\alpha)\hat{\sigma}_{\text{res}}^2 + \alpha\left(\text{Im}\left\{\frac{\hat{\underline{H}}_n^H \underline{Z}_n^\delta}{M}\right\}^2 + \text{Im}\left\{\frac{\hat{\underline{H}}_n^H \underline{Z}_n^\pi}{M}\right\}^2\right), \quad (7)$$

where α is a smoothing factor, and where $\hat{\sigma}_{\text{res}}^2$ is a smoothed estimate that approximates the variance of the residual interference in $\hat{s}_n^\delta$ after MRC combining (*i.e.*, $\sigma_{\text{res}}^2 = \sigma_N^2/2M$).

In a second step, STAR feeds back the estimate of the data signal component $\hat{s}_n^\delta$ (or $\hat{\psi}_n\hat{b}_n$) in a decision feedback identification (DFI) scheme to update the channel estimate using a blind channel identification procedure (for details see [7]):

$$\hat{\underline{H}}_{n+1} = \hat{\underline{H}}_n + \mu\left(\underline{Z}_n^\delta - \hat{\underline{H}}_n\hat{s}_n^\delta\right)\hat{s}_n^\delta \ , \quad (8)$$

where $\hat{\underline{H}}_n$ is the adaptive channel estimate and μ is the adaptation step-size.

The simple DFI scheme of Eqs. (3) and (8) allows coherent detection of the signal component within a sign ambiguity, say $a = \pm 1$, thereby giving[2]:

$$\hat{s}_n^\delta \simeq a\ \psi_n\ b_n \ , \quad (9)$$

$$\hat{b}_n \simeq a\ b_n \ , \quad (10)$$

$$\hat{\underline{H}}_n \simeq a\ \underline{H}_n \ . \quad (11)$$

Without additional processing before binary decision, the resulting blind[3] version of STAR requires differential decoding of DBPSK modulated data to remove the sign ambiguity a. If $\underline{b}_n$ denotes the original information bit sequence before differential coding, then we have:

$$\text{differential modulation} \Rightarrow b_n = \underline{b}_n b_{n-1}, \quad (12)$$

$$\text{coherent detection} \Rightarrow \hat{b}_n = \text{Sign}\left\{\hat{s}_n^\delta\right\} \simeq ab_n, \quad (13)$$

$$\text{differential decoding} \Rightarrow \hat{\underline{b}}_n = \hat{b}_n\hat{b}_{n-1}. \quad (14)$$

If a reference signal with a known sign such as the pilot signal component $\hat{s}_n^\pi$ is used[4] for decision feedback identification from the pilot channel observation vector:

$$\hat{\underline{H}}_{n+1} = \hat{\underline{H}}_n + \mu\left(\underline{Z}_n^\pi - \hat{\underline{H}}_n\hat{s}_n^\pi\right)\hat{s}_n^\pi \ , \quad (15)$$

we obtain a pilot-channel assisted version of STAR where coherent detection of BPSK modulated data can be achieved without a sign ambiguity (*i.e.*, $a = 1$).

We previously reported [7] that the blind version of STAR achieves higher capacity than the pilot-assisted one. On one hand, the pilot allows coherent modulation and detection. However, it requires more power to improve identification, therefore it increases interference and reduces capacity. On the other hand, identification of the channel from a sufficiently powerful data signal is more accurate and avoids the additional interference generated by the pilots. Although this blind scheme degrades BER performance by differential decoding of differentially modulated data, it offers overall a higher capacity due to the reduced interference and better channel estimates.

Here, we attempt to extend the advantage of the blind version of STAR over the pilot-channel assisted one by allowing its implementation with coherently modulated data. To do so, we propose to retain channel identification from the data but to resolve the resulting sign ambiguity a with a much weaker pilot devoted for this sole purpose[5]. We refer to this new pilot as "pilot sign". Note that for the relatively rare intervals of timing acquisition we may use a stronger pilot. In the following, we explain the resulting scheme of STAR, called pilot-sign assisted STAR.

The pilot signal component carries a noisy value of the sign ambiguity a:

$$\hat{s}_n^\pi \simeq a\ \psi_n\ \xi \ . \quad (16)$$

The total amplitude ψ_n is very stable due to power control and renders $\hat{s}_n^\pi$ almost constant. It allows robust long-term averaging of the sign ambiguity, unlike pilot-channel identification, where averaging has serious limitations due to the channel time-variations. Hence, we estimate a by taking the sign of the average of the pilot signal components over consecutive blocks of A samples[6]:

$$\bar{s}_n^\pi = \frac{\sum_{i=0}^{A-1}\hat{s}^\pi_{(\lfloor n/A\rfloor-1)A+i}}{A} \ , \quad (17)$$

$$\hat{a}_n = \text{Sign}\left\{\bar{s}_n^\pi\right\} \ . \quad (18)$$

As shown in the next section, this simple averaging step reduces the sign ambiguity errors even at extremely weak power ratios of the pilot sign and results in a significant gain in capacity due to the negligible excess interference from this new pilot. Note that this scheme applies to pilot-symbol [2],[9] assisted versions as well, thereby significantly reducing the overhead and increasing capacity. We leave this extension to a future work.

[1]These power estimation steps are given for completeness. Alternative procedures could be studied, but that is beyond the scope of this contribution.

[2]A "sign hopping" in the DFI scheme may occur, but the sign ambiguity a is in most cases stable and constant in time.

[3]There is no need for a pilot in this case and Eq. (7) could be easily adapted accordingly.

[4]We actually use $\xi\hat{\psi}$ (or $|\hat{s}_n^\pi|$) which always has the *a priori* known positive sign of the pilot instead of $\hat{s}_n^\pi$ where sign errors could occur due to the residual interference.

[5]As shown later by simulations, the pilot power fractions required by the new technique are extremely weak. Hence, when we tried exploitation of both the pilot and the data channels in channel identification in the initial structures we have tested, we observed that the weak excess power from the pilot could not provide any noticeable improvement.

[6]Other schemes that estimate a using smoothing or an averaging sliding window provide equivalent results.

Coherent demodulation is achieved by eliminating the estimated sign ambiguity from the estimated sequence in Eq. (5), leaving the final bit estimate[7] as:

$$\tilde{b}_n = \hat{a}_n \hat{b}_n \ . \qquad (19)$$

In the next sections we analyze the performance of this new scheme, referred to as pilot-sign assisted STAR, then show its capacity advantage over the blind and pilot-channel assisted versions of STAR.

IV. BER Performance Analysis

For the sake of simplicity, we assume in the following a perfect power control situation (*i.e.*, the total received power is $\psi_n^2 = \psi^2$) and relegate the case of imperfect power control to a future study[8].

The bit-error rate (BER) before FEC decoding is the probability p_e that we make an error on the sign of b_n in $\tilde{b}_n = \hat{a}_n \hat{b}_n$. Since $\hat{a}_n$ and $\hat{b}_n$ are independent, this probability is given by:

$$p_e = P\left(\left\{\tilde{b}_n \neq b_n\right\}\right) = p_e^\sigma(1-p_e^\delta) + p_e^\delta(1-p_e^\sigma) \ , \qquad (20)$$

where:

$$p_e^\delta = P\left(\left\{\hat{b}_n \neq a b_n\right\}\right) \ , \qquad (21)$$

$$p_e^\sigma = P(\{\hat{a}_n \neq a\}) \ . \qquad (22)$$

The probability p_e^δ computes the error on the sign of the data signal component:

$$\hat{s}_n^\delta = \mathrm{Re}\left\{\frac{\hat{\mathrm{H}}_n^H \mathrm{Z}_n^\delta}{M}\right\} = \psi \ a \ b_n + \eta_n^\delta \ , \qquad (23)$$

where η_n^δ is the residual noise at the output of the data MRC combiner of Eq. (3). This probability of a simple antipolar binary decision is given by:

$$p_e^\delta = \frac{1}{2} \ \mathrm{erfc}\left(\sqrt{SNR_{\mathrm{out}}^\delta}\right) \ , \qquad (24)$$

where $SNR_{\mathrm{out}}^\delta$ is the SNR at the output of the data MRC combiner. Using the results of the convergence and performance analyses established in [7], we obtain that:

$$SNR_{\mathrm{out}}^\delta = SNR_{\mathrm{in}} \ \frac{2M}{1+(P+SNR_{\mathrm{in}})\beta^2} \ , \qquad (25)$$

where β^2 is the mean square error of channel identification and is a function of the adaptation step-size, the noise level and the fading rate (*i.e.*, $\beta^2(\mu, \sigma_N^2, f_D T_s)$).

[7]We may also incorporate the estimated sign ambiguity in the DFI scheme with practically the same expected behavior of the algorithm. To keep the analysis simple, we do not pursue this alternative. Notice also that extensions to other digital modulations such as MPSK are *ad hoc*.

[8]Note that power control bit commands are planned to be time-multiplexed with the pilot in third generation standards. The proposed scheme requires that these command bits be transmitted in a different way (*e.g.*, code-multiplexed).

The probability p_e^σ computes the error on the sign of the average pilot signal component $\bar{s}_n^\pi$. Averaging the pilot signal component:

$$\hat{s}_n^\pi = \mathrm{Re}\left\{\frac{\hat{\mathrm{H}}_n^H \mathrm{Z}_n^\pi}{M}\right\} = a \ \xi \ \psi + \eta_n^\pi \ , \qquad (26)$$

over A samples improves the SNR at the output of the pilot MRC combiner, given similarly to Eq. (25) by:

$$SNR_{\mathrm{out}}^\pi = \xi^2 SNR_{\mathrm{in}} \ \frac{2M}{1+(P+\xi^2 SNR_{\mathrm{in}})\beta^2} \ , \qquad (27)$$

by a factor A. This averaging step yields:

$$\bar{s}_n^\pi = \frac{\sum_{i=0}^{A-1} \hat{s}_{n-i}^\pi}{A} = a \ \xi \ \psi + \frac{\sum_{i=0}^{A-1} \eta_{n-i}^\pi}{A} \ , \qquad (28)$$

where η_n^π is the residual noise at the output of the pilot MRC combiner of Eq. (4) before averaging. The probability p_e^σ is therefore given by:

$$p_e^\sigma = \frac{1}{2} \ \mathrm{erfc}\left(\sqrt{A \ SNR_{\mathrm{out}}^\pi}\right) \ . \qquad (29)$$

V. Capacity Evaluation

Using the analysis results established earlier, we first propose simple computation procedures to evaluate and optimize the uplink capacity in terms of the number of users per cell for blind and pilot-assisted (*i.e.*, channel and sign) array-receivers at different qualities of service and fading rates (*i.e.*, operating conditions). Second, we provide and discuss optimized capacity evaluation results and compare the performance of the above array-receiver versions.

A. Computation Procedure

Capacity computation procedures for pilot-assisted and blind array-receivers, shown in Figs. 1 to 3, have the same general structure. For a specified BER value before channel decoding, say P_e (*i.e.*, quality of service), all procedures initialize the capacity, C, and increment it until the corresponding probability of error exceeds the required BER value P_e. C is then reduced to the largest value for which $p_e \leq P_e$. However, the three procedures differ in steps 2.2 and 2.4 which compute the noise variance σ_N^2 and the BER value, respectively.

In step 2.2, we use the fact that each in-cell user is received with a total received power of $(1+\xi^2)\psi^2$ for pilot-assisted (*i.e.*, channel and sign) and ψ^2 for blind array-receivers respectively. Hence the in-cell interference powers before despreading resulting from C in-cell users are $C(1+\xi^2)\psi^2$ and $C\psi^2$, respectively. Assuming that the outcell-to-incell interference ratio is η^2, the total received interference powers before despreading are $C(1+\xi^2)(1+\eta^2)\psi^2$ and $C(1+\eta^2)\psi^2$, respectively. Step 2.2 in Figs. 1 to 3 hence computes the received interference

1. Initialize capacity $C = 0$.
2. Start computation loop:
   - 2.1. increment capacity $C = C + 1$,
   - 2.2. compute noise variance $\sigma_N^2 = \frac{C\nu^2(1+\xi^2)(1+\eta^2)}{L}$,
   - 2.3. compute misadjustment $\beta^2(\mu\xi^2, \sigma_N^2/\xi^2, f_D T_s)$,
   - 2.4. compute BER:
     - 2.4.1 compute data output SNR $SNR_{\text{out}}^{\delta} = SNR_{\text{in}} \frac{2M}{1+(P+SNR_{\text{in}})\beta^2}$,
     - 2.4.2 compute $P_e = \frac{1}{2}\,\text{erfc}\left(\sqrt{SNR_{\text{out}}^{\delta}}\right)$,
   - 2.5. if $p_e \leq P_e$ goto 2.1, else exit loop.
3. Decrement capacity $C = C - 1$.

Fig. 1. Computation procedure of capacity $C^{pc}(p_e, \mu, \xi^2)$ for pilot-channel assisted array-receivers (*i.e.*, coherent detection) at a specified fading rate $f_D T_s$.

power after despreading with a processing gain denoted by L assuming perfect power control (*i.e.*, $\psi^2 = 1$) for pilot-channel, blind and pilot-sign assisted array-receivers, respectively. The factor ν^2 in the expressions for the interference refines those established in [7] by taking into account the effect of intra-path time-delay mismatch, the speech or data activity factor and the probability of outage [12].

In step 2.4, for blind array-receivers we compute the BER value p_e of coherent detection and differential decoding (see Fig. 2) by taking into account error propagation in differential decoding. On the other hand, for pilot-channel array-receivers we compute the BER value p_e of simple coherent detection (see Fig. 1). However, for pilot-sign assisted array-receivers we compute the BER value p_e of coherent detection and sign-ambiguity compensation from the pilot-sign (see Fig. 3). Notice also that step 2.3 is different for pilot-channel array-receivers (see Fig. 1), because identification is made with a step-size $\mu\xi^2$ and noise level of σ_N^2/ξ^2 seen from the pilot-channel.

As shown next, the procedures of Figs. 1 to 3 allow the computation and the optimization of capacity over the adaptation step-size values and the pilot-to-data power ratios (for details see [7]).

B. Results and Discussion

Using the capacity computation procedures described above, we compare the best capacity results for pilot-assisted and blind array-receivers. We also give the corresponding optimal values of the step-size and the pilot-to-data power ratio at different qualities of service and fading rates. We consider the case of $M = 2$ antennas and $P = 1$ path. Three Doppler frequency values of 10, 100 and 200 Hz are examined[9], corresponding to three representative mobile speeds of almost 5, 50 and 100 Kmph respectively (*i.e.*, pedestrian, urban and highway) at a carrier frequency of 1.9 GHz. These Doppler frequencies correspond

[9]To specify operating conditions in practice as indicated in [7], a Doppler frequency estimator (*e.g.*, [10]) can be used to estimate $\hat{f}_D$ while $\hat{\sigma}_N^2$ and $\hat{\psi}^2$ can be both estimated from the received signals.

1. Initialize capacity $C = 0$.
2. Start computation loop:
   - 2.1. increment capacity $C = C + 1$,
   - 2.2. compute noise variance $\sigma_N^2 = \frac{C\nu^2(1+\eta^2)}{L}$,
   - 2.3. compute misadjustment $\beta^2(\mu, \sigma_N^2, f_D T_s)$,
   - 2.4. compute BER:
     - 2.4.1 compute data output SNR $SNR_{\text{out}}^{\delta} = SNR_{\text{in}} \frac{2M}{1+(P+SNR_{\text{in}})\beta^2}$,
     - 2.4.2 compute $p_e^{\delta} = \frac{1}{2}\,\text{erfc}\left(\sqrt{SNR_{\text{out}}^{\delta}}\right)$,
     - 2.4.3 compute $p_e = 2\, p_e^{\delta}\, (1 - p_e^{\delta})$,
   - 2.5. if $p_e \leq P_e$ goto 2.1, else exit loop.
3. Decrement capacity $C = C - 1$.

Fig. 2. Computation procedure of capacity $C^{b}(p_e, \mu, \xi^2)$ for blind array-receivers (*i.e.*, coherent detection and differential decoding) at a specified fading rate $f_D T_s$.

1. Initialize capacity $C = 0$.
2. Start computation loop:
   - 2.1. increment capacity $C = C + 1$,
   - 2.2. compute noise variance $\sigma_N^2 = \frac{C\nu^2(1+\xi^2)(1+\eta^2)}{L}$,
   - 2.3. compute misadjustment $\beta^2(\mu, \sigma_N^2, f_D T_s)$,
   - 2.4. compute BER:
     - 2.4.1 compute data output SNR $SNR_{\text{out}}^{\delta} = SNR_{\text{in}} \frac{2M}{1+(P+SNR_{\text{in}})\beta^2}$,
     - 2.4.2 compute pilot output SNR $SNR_{\text{out}}^{\pi} = \xi^2 SNR_{\text{in}} \frac{2M}{1+(P+\xi^2 SNR_{\text{in}})\beta^2}$,
     - 2.4.3 compute $p_e^{\delta} = \frac{1}{2}\,\text{erfc}\left(\sqrt{SNR_{\text{out}}^{\delta}}\right)$,
     - 2.4.4 compute $p_e^{\sigma} = \frac{1}{2}\,\text{erfc}\left(\sqrt{A\; SNR_{\text{out}}^{\pi}}\right)$,
     - 2.4.5 compute $p_e = p_e^{\sigma}\, (1 - p_e^{\delta}) + p_e^{\delta}\, (1 - p_e^{\sigma})$,
   - 2.5. if $p_e \leq P_e$ goto 2.1, else exit loop.
3. Decrement capacity $C = C - 1$.

Fig. 3. Computation procedure of capacity $C^{ps}(p_e, \mu, \xi^2)$ for pilot-sign assisted array-receivers (*i.e.*, coherent detection) at a specified fading rate $f_D T_s$.

to fading rates (*i.e.*, $f_D T_s$) of almost 5.2×10^{-4}, 5.2×10^{-3} and 10^{-2} respectively at a data baud rate of 19.2 Kbps. The static-channel case (*i.e.*, $f_D = 0$ Hz) is included as a reference. Independent Rayleigh fading of different users' signals is simulated using Jakes' model [11]. We select a processing gain $L = 64$ in a system with bandwidth of 1.25 MHz and an outcell-to-incell interference ratio $\eta^2 = 2.28$. Taking into account the effect of time-delay mismatch between square chip pulses, a speech activity factor of 45% with power reduction of 1/8 in silence and a probability of outage of 0.01 [12], we derive a value for ν^2 of 1.15.

Figs. 4 and 5, which provide the evaluation results of pilot-channel and blind array-receivers reported in [7], are given here for reference. Although the number of multipaths and the outcell-to-incell interference ratio are different from [7], these figures lead to the same conclusions. Regarding the capacities achievable, these figures still suggest that blind array-receivers outperform pilot-assisted versions in almost all the situations studied, except for

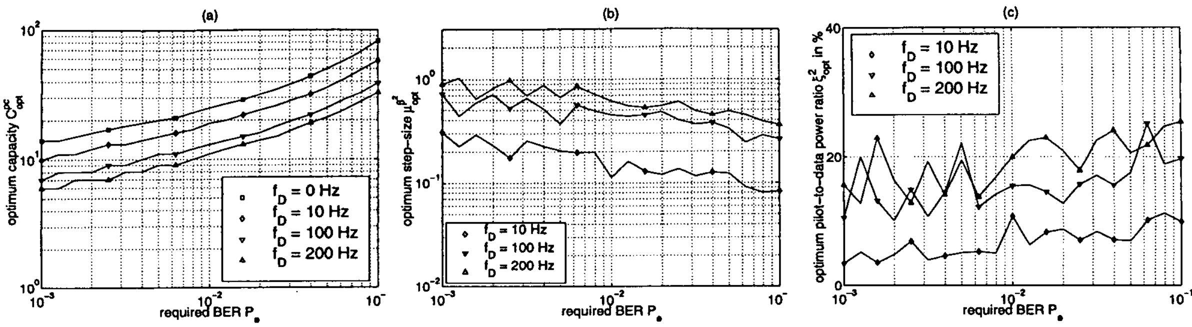

Fig. 4. Evaluation results of pilot-channel assisted array-receiver versus the required BER P_e for different values of f_D. (a): optimum capacity C^{pc}_{opt}. (b): optimum step-size $\mu^{\beta^2}_{\text{opt}}$. (c): optimum pilot-to-data power ratio ξ^2_{opt}.

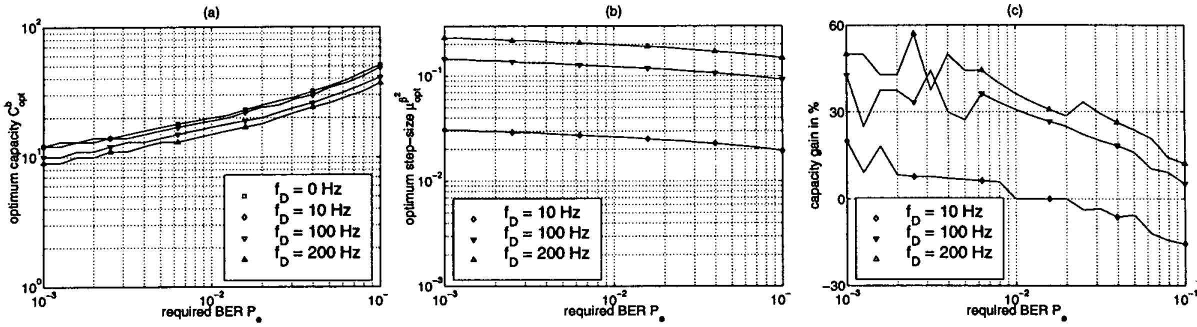

Fig. 5. Evaluation results of blind array-receiver versus the required BER P_e for different values of f_D. (a): optimum capacity C^{b}_{opt}. (b): optimum step-size $\mu^{\beta^2}_{\text{opt}}$. (c): gain in capacity over pilot-channel assisted array-receiver.

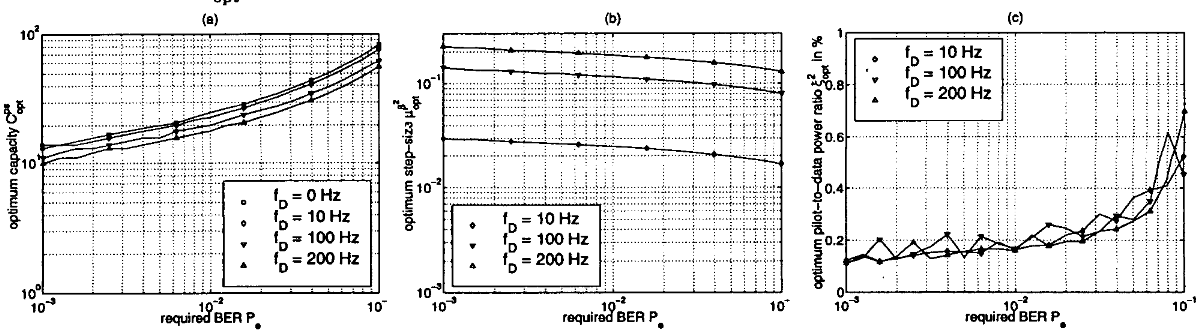

Fig. 6. Evaluation results of pilot-sign assisted array-receiver versus the required BER P_e for different values of f_D. (a): optimum capacity C^{ps}_{opt}. (b): optimum step-size $\mu^{\beta^2}_{\text{opt}}$. (c): optimum pilot-to-data power ratio ξ^2_{opt}.

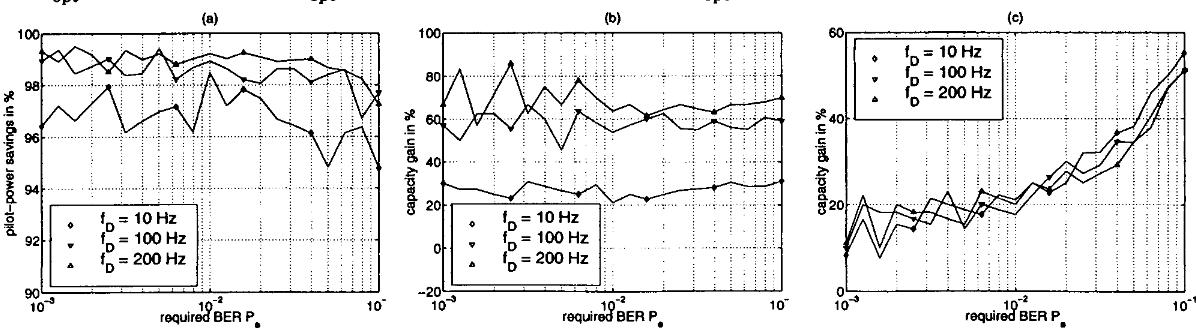

Fig. 7. Key performance improvements of pilot-sign assisted array-receiver versus the required BER P_e for different values of f_D. (a): pilot-power savings over pilot-channel assisted array-receiver. (b): gain in capacity over pilot-channel assisted array-receiver. (c): gain in capacity over blind array-receiver.

the case of large BER values required at low fading rates. They also suggest that the gain in capacity with blind array-receivers is more significant at higher fading rates and smaller BER values. The curves of the optimal step-size (see Figs. 4b and 5b) and the optimal pilot power ratio (see Fig. 5c) as well as the gain in capacity (see Fig. 4c) are almost the same as in [7].

Fig. 6 shows the new evaluation results of the proposed pilot-sign assisted array-receiver. Averages over the pilot-channel MRC combiner in Eq. (17) are calculated over $A = 1000$ samples[10]. Fig. 6a shows that this scheme almost reaches the upper limit on capacity of coherent detection (*i.e.*, static channel for $f_D = 0$ Hz), when the Doppler is slow as intended. It suffers from only a small performance degradation in capacity at fast Doppler. For a wide range of BER values, Fig. 6b indicates that almost constant values of the optimal step-size can be selected around 2×10^{-2}, 10^{-1} and 2×10^{-1} respectively to the Doppler frequencies considered. Fig. 6c shows that the pilot power ratio required for the pilot-sign array receiver is in a range as weak as 10^{-3} for a wide range of BER values. This ratio does not change significantly with the Doppler and increases at higher BER values.

Fig. 7 shows in more detail the key performance improvements of the proposed pilot-sign assisted array-receiver over the pilot-channel assisted and blind array-receivers. Fig. 7a indicates that pilot-power savings with the new scheme are as high as 96 to 99 % compared to the pilot-channel assisted array-receiver. The capacity gain over this scheme shown on Fig. 7b is significant and increases from around 30 % for slow Doppler to about 60 to 70 % for fast Doppler. On the other hand the gain in capacity of the new scheme over the blind array-receiver shown on Fig. 7c does not change noticeably with the Doppler, but increases from 10 to 50 % when the required BER increases from 10^{-3} to 10^{-1}.

C. Validation: Preliminary Results

To complement this self-contained analysis, we are attempting to validate the theoretical results obtained above with simulations using a capacity evaluation tool previously developed [12]. The tool populates a multi-cellular system with spatially uniformly distributed mobiles up to the capacity of the cell and ensures that the received SNR meets the required value. This ongoing work, though computationally complex, should indicate whether it is possible to avoid the processing necessary for capacity evaluation and optimization by simulation.

Recent preliminary results obtained in this direction are very encouraging. For the same environment described above and regardless of the array-receiver scheme, simulation results with a mobile speed of 1 Kmph indicate that $P_e \simeq 0.08$ is required to achieve a BER of 10^{-3} after FEC decoding. They also provide a measured outcell-to-incell interference ratio $\eta^2 \simeq 1.32$. The theoretical results computed again with these values along with the simulated ones are summarized in Tab. 1.

voice @ 9.6 Kbps	analysis		simulation	
	C_{opt}	ξ^2_{opt}	C_{opt}	ξ^2_{opt}
pilot-channel	85	5%	80	10%
blind	59	0%	52	0 %
pilot-sign	99	0.5%	87	1%

Tab. 1. Voice call (*i.e.*, 9.6 Kbps) capacities and pilot power fraction results from analysis and simulation in 1.25 MHz.

data @ 144 Kbps	analysis		simulation	
	C_{opt}	ξ^2_{opt}	C_{opt}	ξ^2_{opt}
pilot-channel	12	1.3%	12	2.5%
blind	6	0%	5	0 %
pilot-sign	13	0.5%	13	0.6%

Tab. 2. Data call (*i.e.*, 144 Kbps) capacities and pilot power fraction results from analysis and simulation in 5 MHz.

The two sets of results lie in the same range within reasonable accuracy margins and provide the same capacity ranking, despite the fact that power control is assumed perfect in the analysis and has an error with standard deviation of 1 dB in the simulations. They also confirm that the pilot-sign array-receiver can offer a higher capacity with a very low pilot power.

In another set of simulations, we tested a data link of 144 Kbps with a mobility of 1 Kmph in a 5 MHz system with $P = 3$ equal-power paths and two $M = 2$ antennas. We assumed continuous transmission and a required BER after FEC decoding of 10^{-5}, and fixed $A = 768$. The theoretical and experimental results are summarized in Tab. 2. Again they confirm that the analysis results fit with those derived by simulations and that the pilot-sign array-receiver can offer a higher capacity with a very low pilot power. Validation of other configurations in wideband environments is continuing.

As mentioned earlier, the proposed pilot-sign technique combines with pilot symbols [2],[9] as well. Current analytical and experimental works suggest that the pilot-sign versions perform nearly as well as the pilot-channel versions studied in this paper. These results will be analyzed and reported in detail in a future contribution.

In general, the optimum results provided in this paper require a perfect estimate of the Doppler frequency. We are presently assessing the sensitivity of these results to errors in Doppler frequency estimation [10]. Additionally, these results assume perfect timing. We expect the incorporation of synchronization to further favor identification from a stronger data channel. We will report on the sensitivity of the studied array-receivers to multipath time-delay estimation errors in the future.

[10]The number of samples A can be increased at will for the own benefit of the array-receiver, but the relative improvement saturates very quickly. The need for a larger memory and the possible risk of a more-lasting sign-error propagation due to sign hopping limit this number in practice.

VI. Conclusions

In this contribution we proposed a new type of pilot-assisted array-receiver, called pilot-sign, which requires simple modifications to the pilot-channel assisted-receivers recommended in the emerging wideband CDMA standards. The resulting pilot-sign assisted array-receiver performs blind channel identification from the data channel within a sign ambiguity for BPSK signals and uses the pilot for the sole purpose of sign estimation. We also extended the performance analysis and the capacity computation procedure proposed in a previous work to the new scheme to allow the evaluation and the optimization of its capacity. Optimal step-size values and pilot power ratios can be readily obtained. Results suggest that the new pilot-sign assisted array-receivers require pilot-power ratios as weak as a fraction of a percent for a wide range of quality of service, thereby offering about 96 to 99 % savings in the pilot power compared to pilot-channel assisted array-receivers. The resulting uplink capacity gain over these receivers increases from about 30 % for a slow Doppler to about 60 to 70 % for a fast Doppler. The new pilot-sign scheme also outperforms blind array-receivers in capacity, the gain increasing from about 10 to 50 % when the required BER increases from 10^{-3} to 10^{-1}. The reduction in pilot power is considered to be applicable to the downlink as well. We will report on those results in the near future.

References

[1] A.J. Viterbi, *CDMA Principles of Spread Spectrum Communication*, Addison-Wesley, 1995.

[2] J.K. Cavers, "An analysis of pilot symbol assisted modulation for Rayleigh fading channels", *IEEE Transactions on Vehicular Technology*, vol. 40, no. 4, pp. 686-693, November 1991.

[3] F. Ling, "Coherent detection with reference-symbol based channel estimation for direct sequence CDMA uplink communications", *Proc. of IEEE VTC'93*, 1993, pp. 400-403.

[4] F. Ling, "Pilot assisted coherent DS-CDMA reverse-link communications with optimal robust channel estimation", *Proc. of IEEE ICASSP'97*, 1997, vol. 1, pp. 263-266.

[5] F. Ling, "Optimal reception, performance bound, and cutoff rate analysis of reference-assisted coherent CDMA communications with applications", *IEEE Transactions on Communications*, vol. 47, no. 10, pp.1583-1592, October 1999.

[6] P. Schramm, "Analysis and optimization of pilot-channel-assisted BPSK for DS-CDMA systems", *IEEE Transactions on Communications*, vol. 46, no. 9, pp. 1122-1124, September 1998.

[7] S. Affes and P. Mermelstein, "Comparison of pilot-assisted and blind CDMA array-receivers adaptive to Rayleigh fading rates", *Proc. of IEEE PIMRC'99*, 1999, vol. 3, pp. 1186-1192.

[8] S. Affes and P. Mermelstein, "A new receiver structure for asynchronous CDMA : STAR - the spatio-temporal array-receiver", *IEEE Journal on Selected Areas in Communications*, vol. , no. 16, pp. 1411-1422, October 1998.

[9] C. D'Armours, M. Moher, and A. Yongaçoğlu, "Comparison of pilot-symbol assisted and differentially detected BPSK for DS-CDMA systems employing RAKE receivers in Rayleigh fading channels", *IEEE Transactions on Vehicular Technology*, vol. 47, no. 4, pp. 1258-1267, November 1997.

[10] H. Hansen, S. Affes, and P. Mermelstein, "A Rayleigh Doppler frequency estimator derived from ML theory", *Proc. of IEEE Signal Processing Workshop on Signal Processing Advances in Wireless Communications SPAWC'99*, 1999, pp. 382-386.

[11] W.C. Jakes, Ed., *Microwave Mobile Communications*, John Wiley & Sons, 1974.

[12] A. Jalali and P. Mermelstein, "Effects of diversity, power control, and bandwidth on the capacity of microcellular CDMA systems", *IEEE Journal on Selected Areas in Communications*, vol. 12, no. 5, pp. 952-961, June 1994.