Capacity Evaluation of Fixed Beams in a WCDMA System using channel estimation based on
P-CPICH♣

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Abstract—A fixed multi-beam system that uses the Primary-
Common Pilot Channel (P-CPICH) as a phase reference for
channel estimation and demodulation in WCDMA is evaluated
in a dynamic radio network simulator. The impact of the angular
spread on the downlink system performance is analyzed. Fur-
thermore, a scrambling code allocation strategy and an adaptive
load-dependent power tuning algorithm for the P-CPICH are
proposed. Extensive simulation studies are carried out to evaluate
the capacity gains of 3-sector sites where each site is equipped
with 1, 2 or 4 beams in a typical urban radio channel. Moreover
an alternative antenna configuration consisting of 6-sector sites
where each sector is equipped with 2 beams is evaluated.

I. INTRODUCTION

Conventional wireless systems make use of omni-directional
or sectorized antenna system. The major drawback of such
antenna system is that electro-magnetic energy, intended to
particular user in a certain location, is radiated unnecessarily in
every direction within the entire cell, causing thus interference
to other users in the system. One way to limit this source of
interference and direct the energy to the desired user, is
to introduce smart antennas. This is a well known technique
that improves the coverage and the capacity of a wireless
communication system [1].

The first 3GPP release of WCDMA system envisaged the
creation of specific common channels e.g. Secondary Common
Pilot Channel (S-CPICH), transmitted over a specific area
of the cell in order to assist the UE to estimate the radio
channel. It is not clear if the S-CPICH will be included in
future 3GPP WCDMA releases. Consequently the introduction
of smart antennas in WCDMA necessitates a robust channel
estimation that can be done using other common channels such
as the Primary Common Pilot Channel (P-CPICH), which is
transmitted in the entire cell.

The main advantage of such method is to eliminate the
need of the S-CPICH thus potentially decreasing the intra-
and inter-cell interference. The main drawback of the scheme
is: 1) the antenna gain of the primary P-CPICH is lower than
the narrow beams used for data transmission, 2) the channel
Impulse Response (IR) of the sector covering beam and the
narrow beams where the user specific data is transmitted, may
be considerably different. The mismatch between the wide
and narrow beam IRs becomes increasingly different in the
presence of larger Angular Spread (AS). It not clear how this
mismatch would affect the system performance.

Although earlier studies [1], [2] quantified the gains of
Fixed Beam (FB) systems in WCDMA using dynamic sys-
tem simulators, the impact of angle spread, scrambling code
allocation and the power settings of the common channels
were largely neglected. Other published work investigating the
system performance of fixed multi-beam systems in WCDMA
can be found in [3]. In these studies, the evaluation was
conducted by means of quasi-static system simulation and in
most of these studies a simplified channel model was assumed.
Furthermore, the aspect of radio resource management was
neglected (e.g. power control, handover). Recently, [4] took
into account major RRM functionalities, while a mean AS was
assumed, no optimal scrambling code allocation strategies nor
optimal power settings of the common channel were studied.
Finally, an extensive system capacity evaluation of FB systems
using S-CPICH was conducted in [5].

The novelty of this paper is threefold:
• P-CPICH is used as a phase reference for channel estima-
tion and demodulation in a fixed multi-beam system. The
performance is evaluated using a dynamic radio network.
• A scrambling code allocation technique is suggested.
• A power tuning method for the common channel is
presented and evaluated.

II. P-CPICH FOR CHANNEL ESTIMATION

Assuming a plane wave incident in the horizontal plan on
a Uniform Linear Array (ULA) from an angle \( \theta \) relative to
the axis of the array, it can be shown that the array factor
(or antenna gain) of a ULA consisting of \( N \) Antenna Element
(AE) is given by:

\[
g(\theta) = \omega_i^H \alpha(\theta)
\]

where

\[
\alpha(\theta) = \left[ 1 \ e^{-j\beta x_1 \cos \theta} \ldots \ e^{-j\beta x_{N-1} \cos \theta} \right]^H
\]

is the spatial signature, and

\[
\omega_i = \left[ \omega_{i,0} \ldots \omega_{i,N-1} \right]^H
\]

is the weight vector of the \( i \)th beam. \( \beta = 2\pi/\lambda \) is the phase
propagation factor, and \( \lambda \) is the wavelength.
In case of a FB system, the number of the weight vectors is fixed and usually equal to the number of the antenna elements in the ULA. The FB weight vectors are generated by a Beam Forming Network (BFN) that produces $N$ orthogonal beams using $N$ antenna elements. Let us define the $N \times N$ BFN Matrix (BFNM) as $T = [\omega_0 \omega_1 \ldots \omega_{N-2} \omega_{N-1}]$. $T$ comprises of the weight vectors of all the narrow fixed beams. The most commonly used techniques for implementing a BFN is the use of cascaded hybrid couplers known as the Butler matrix, which is simply a realization of the Discrete Fourier Transform (DFT), so the array weight are given by:

$$\omega_{i,m} = e^{-j2\pi mi} , \ i \in \{0, \ldots, N - 1\}$$ (4)

The BFNM is then equal to the unitary discrete Fourier transform matrix. Let $\omega_C$ denote the weight vector of the sector covering beam where common channels such P-CPICH are transmitted on. All elements of $\omega_C$ are set to zero except for one of them. This implies that the common channels are transmitted on one of the AE of the ULA. Consequently there is a phase difference between the array factor of the common and dedicated beams, which may lead to erroneous channel estimation [6], [7]. This problem is rectified if downlink phase coherency is used.

**A. Common and Dedicated Channel Mismatch**

Two types of channels are transmitted in a cell. The first one consists of the Common Channel (CCH) signalling (including the P-CPICH) and is transmitted through the wide beam using a single antenna element (to cover the whole cell). The second type consists of the Dedicated Channel (DCH) which carries all higher layer information intended for a specific user, and is transmitted over a narrow beam.

In WCDMA, the P-CPICH is generally used by the UEs for channel estimation in sectorized systems, where each sector is associated with its unique P-CPICH. In a FB system, the user data is transmitted using a narrow beam and the P-CPICH is transmitted on a sector covering wide beam. This is illustrated in Figure 1 where as an example four scatterers are shown. Moreover, the narrow beam may enhance the signal from some scatterers and attenuate from others. Consequently the channel IR of the wide beam may differ from the narrow beam channel IR, experienced at the UE. The smaller the angular spread is, the higher the correlation will be (between the wide beam and narrow beam channel IRs).

Let $h_{c,m}(t;\tau)$ and $h_{m,m}(t;\tau)$ be the time-varying channel impulse response at time instant $t$ of the link $m$ for the CCH and DCH, respectively. The UE will estimate the channel on the P-CPICH. For the received signal on the P-CPICH, the data is matched to the P-CPICH estimate. As it shown in Figure 2(a), the received CCH signal is matched to the correct IR, (i.e., $f_{c}(t;\tau) = h_{c,m}^{\ast}(t;\tau)$, where $f_{c}(t;\tau)$ is the matched filter IR for the CCH). Whereas the received signal from the DCH (transmitted on the narrow beam) is matched to the channel IR estimated on the wide beam channel as shown in Figure 2(b), ($f_{m}(t;\tau) = f_{e}(t;\tau) = h_{c,m}^{\ast}(t;\tau)$, where $f_{m}(t;\tau)$ is the matched filter IR for the DCH). This will result in a phase mismatch between the DCH and CCH that impacts the system performance in particular for large AS as illustrated in Figure 1.

**III. System Setup**

The simulated area consists of a central site and two surrounding tiers of sites. The total number of sites is 19. Each site comprises of 3 or 6 sectors (i.e. cells). Users are dynamically generated in the central site and the first tier (which consists of 6 sites). The second tier consists of 12 sites where no users are generated. Instead the BSs power of the second tier is time varying and is modelled as a random walk with upper and lower bounds determined by the 90th and 10th percentile of the transmitted power allocated to the BSs in the central and the first tier sites.

The site-to-site distance is 3 km. Note that the simulation tool is similar to the one used in [1]. On each iteration of the main loop, the simulator time is increased by the duration of one frame and all radio network algorithms are executed, except for the power control which is executed on a slot level. The most relevant system and simulation parameters are summarized in Table I.

**A. Propagation Environment**

The propagation model used is the COST 259 channel model [8], which is a spatial temporal radio propagation model...
that includes the effect of fast and slow fading. The COST 259 version used in the current system simulator yields an instantaneous Power Delay Profile (PDP) $P_m$, the Rice factor $r_m$, and the angular spread $\sigma_m$ for the $m$th link in the system. The COST 259 can models several radio environments. Here we investigate the Typical Urban (TU) channel model.

In an urban environment, the spatial distribution of the signal power is known as the Power Azimuth Spectrum (PAS)\(^2\), is described by a Laplacian pdf [9], that is:

$$f(\theta_m, \sigma_m) = \frac{1}{\sqrt{2\pi\sigma_m}} \exp \left(-\frac{\sqrt{2}(\theta - \theta_m)}{\sigma_m}\right)$$

(5)

where $\theta_m$ denotes the nominal direction to the mobile. Given the PAS the user dependent channel correlation matrix is given by

$$R(\theta_m, \sigma_m) = \int_{-\infty}^{\infty} a(\theta) a^H(\theta) f(\theta|\theta_m, \sigma_m) d\theta$$

(6)

From Equation 6, the channel Impulse Response (IR) of the $m$th link can be easily derived.

Let the $r$th rows of $Z_m \in \mathbb{C}^{M \times L}$ denote a realization of the channel impulse response from the $r$th antenna to the $m$th link. $L$ denotes the upper bound of the channel order and, $M$ is the total number of antennas per site. The elements of $Z_m$ are obtained by sampling from $NL$ independent Rayleigh fading processes and each row is multiplied by the same power delay profile $p_m$. Let $m$ and $n$ denote two links connected to the same site $s$. Let $h_{m,n}$ denote the IR as seen by link $m$ when the site $s$ transmits to link $n$ using the transmit weight vector $w_n \in \mathbb{C}^{N \times 1}$. $h_{m,n}$ is given by

$$h_{m,n} = w^H_n \left( R^{1/2}(\theta_m, \sigma_m) Z_m + \rho_m \right)$$

(7)

where

$$\rho_m = \frac{r_m}{1 + r_m} e^{j2\pi d_m/\lambda} \otimes v^H$$

(8)

$\rho_m$ is the Rice component of the channel IR. $R^{1/2}$ is the square root of the matrix $R$ (i.e. $R^{1/2} R^{1/2} = R$), $\otimes$ denotes the Kroneker product, $d_m$ is the relative distance between the BS and the UE, and the vector $v = [1, 0_1 \times (L-1)]^H$ ensures that the Rice component appears on the first tap of the channel IR.

B. Receiver Structure

Each mobile is assumed to have a single receive antenna. Furthermore, perfect channel estimates of the common channel transmitted from the sector covering beam is assumed in the terminals. The terminals employ a conventional Maximum Ratio Combining (MRC) receiver matched to the common channel, i.e. a RAKE receiver with 10 fingers for the TU channel model. Power Control (PC) is also implemented and consists of inner and outer loop. The inner loop power control and the fast fading act on slot level. The inner loop PC assumes ideal Signal to Interference plus Noise Ratio (SINR) estimation (i.e. no measurement error is considered). After the slot loop, the instantaneous SINR are averaged linearly over the TTI and mapped to a Block Error Probability (BLEP). Each block is then classified as erroneous or not, which gives the block error rate (BLER) estimates. The BLER estimates are used by the outer loop algorithm in order to decide if the SINR target should be increased or decreased.

C. Orthogonality factor

As shown in [10], the SINR is a function of the orthogonality factor. The expected SINR for the $m$th user after despreading is generally modelled as follows

$$\text{SINR}_m = \frac{N_m G_m P_m}{\alpha_m G_m P_m + I_m + N_0}$$

(9)

where $N_m$, $G_m$, $P_m$ and $N_0$ denote the spreading factor, the path gain, the transmitted power to the $m$th user, and the thermal noise respectively. $P_t$ is the total base station power allocated to signals using the same scrambling code as $m$. $I_m$ is the interference from the non-orthogonal signals originating from the own cell and other cells. Finally $\alpha_m$ is the downlink orthogonality factor, which represents the fraction of the wide band received power of the orthogonal signals causing interference to user $m$. It can be shown (see [10]) that the orthogonality factor may be written as follows:

$$\alpha_m[k] = \sum_{l=-L+1}^{n_F-1} \frac{|r_{m,l}[k]|^2}{|r_{m,0}[k]|^2}$$

(10)

where $\{r_{m,l}[k] : l = -L + 1, \ldots, n_F - 1\}$ is the IR of the combined effect of the transmit weights, radio channel and the receiver filter at time instance $k$. $n_F$ is the number of taps of the receiver filter.

D. Antenna Configuration:

Two antennas configurations are investigated. The first assumes 3 sectors (3Sec) per site while 6 sectors (6Sec) per site are assumed in the second case. Each of these sectors comprises of an antenna array consisting of $N$ antenna elements forming a ULA. The distance between two adjacent antenna elements within the same ULA is $d$. The central antenna element of each ULA form a uniform circular array with radius $r$. Finally, the orientation of the ULAs are on

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sites</td>
<td>19</td>
</tr>
<tr>
<td>Site type</td>
<td>3- or 6-sectors</td>
</tr>
<tr>
<td>Cell radius [m]</td>
<td>1000</td>
</tr>
<tr>
<td>Number of Antenna Element/sector</td>
<td>1, 2 or 4</td>
</tr>
<tr>
<td>Number of beams/sector</td>
<td>1, 2 or 4</td>
</tr>
<tr>
<td>Channel model</td>
<td>COST259</td>
</tr>
<tr>
<td>Number of RAKE fingers</td>
<td>10</td>
</tr>
<tr>
<td>SF of the 64 kbps user</td>
<td>32</td>
</tr>
<tr>
<td>Max BS output power [W]</td>
<td>20, 40 or 80</td>
</tr>
</tbody>
</table>
the tangent (i.e. perpendicular to the radius) of the circle. Fig. 3 shows the antenna configuration for a 6-sector site. The antenna diagrams of the 2FB in a 6Sec configuration and 4FB in a 3Sec configuration are shown as an example in Figs. 4(a) and 4(b), respectively. The antenna diagram of the broad beam (denoted as AE) is plotted in dotted lines in Fig 4 for both cases. Unless otherwise specified, 3 sectors per site is the default configuration.

E. Scrambling code allocation

In WCDMA, multiple access is performed in two steps. First the data is spread (i.e. channelized) with a channelization code belonging to the OVSF code family. The second step consists of scrambling the data with a scrambling code belonging to the Gold code family. Each user is associated with a unique scrambling code and every BS is associated with one or more unique scrambling codes. The channelization code tree has a limited number of OVSF codes. Hence when the tree is occupied either new users are blocked or a new scrambling code should be opened. Most studies have focused on OVSF code re-assignment (or allocation) in order to reduce the blocked users due to channelization code shortages. Recently, [11] studied the impact of opening a secondary scrambling code in WCDMA systems equipped with a single antenna. The method consisted simply of allocating new users to the secondary scrambling code when the code tree of the primary scrambling code was fully occupied; code reassignment was not investigated in [11].

A simple SC allocation method would be to allocate a unique scrambling code for each beam. Unfortunately this method requires a S-CPICH associated with each narrow beam. An alternative solution is to open a new SC if there is a need to do so. In this scheme the users requiring high downlink transmit power are assigned the first SC. This simply derives from the fact that the P-CPICH and other common channels are transmitted on the primary SC. If a user requiring a high DL power was allocated to a secondary SC then the user will observe an elevated level of interference compared to the case if the user was allocation to the primary SC. This strategy is called the “power based” (PB) scrambling code allocation and can be summarized as follows:

1) Sort the users in a decreasing order according to their downlink transmit power.
2) Allocate users beginning from the top of the list to the primary SC until all channelization codes are assigned.
3) Use secondary SCs and assign the required channelization codes for the remaining users. Use as few secondary SCs as possible as long as all the users on the list have been allocated the desired channelization codes.
4) Periodically monitor the downlink power of the users and goto Step 1.

F. Mobility & Traffic Models

The mobile users are uniformly distributed in the cells. The average user speed is 3 km/h with small variations around the mean value. A poisson distribution time of arrival is assumed for the users. Furthermore, the user session time is exponentially distributed with mean holding time of 5s. The data are transmitted in a continuous stream (no TCP) using a 64kbps RAB (Radio Access Bearer) with retransmissions.

G. Performance Measure

The total system throughput is defined by the sum of correctly delivered bits to all users connected to the central site divided by the simulation period and the number of simulated
cells in the central site. The user bit rate is given by the ratio of the total received bits over the length of the user’s session time. The Quality of Service (QoS) depends on the user bit rate. The QoS is met when the average bit rate of all users is greater than 55kbps. The system capacity is defined as the total system throughput when the QoS is met.

IV. RESULTS

In this section the performance of various antenna configurations is presented. The impact of tuning the power of the common channels is shown, and finally the impact of the AS and the antenna configurations are investigated.

The system capacity for TU channels is shown in Table II where the capacity gain of 2FB and 4FB relative to the 1FB in a 3Sec configuration is summarized. While the 2FB case offered 50% capacity gain, the 4FB case offered only 80% gain capacity. In fact, as the number of beams increases then the mismatch between the channel IR from the broad and narrow beams differs substantially due to AS.

<table>
<thead>
<tr>
<th>FB per sector</th>
<th>Relative Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>1.8</td>
</tr>
</tbody>
</table>

TABLE II
REFERENCE CAPACITY GAIN FOR A 3Sec CONFIGURATION.

A. Primary CPICH Tuning

The percentage of the power allocated to the common channels in WCDMA impacts the downlink system capacity. In fact [12] showed how the system capacity related to the power used for common channels in a FB system. Hence it is crucial to ensure a good quality of the received common channel signal without necessarily setting its value for the worse case as it is classically done in radio planning tool. Here a tuning algorithm for the power of the P-CPICH is proposed and evaluated. The proposed algorithm applies power control to the transmitted P-CPICH signal from all the BSs such that 95% of the users have their CIR greater than −18 dB. In fact a target of −18 dB is considered more than adequate to detect the cell and perform measurements on the P-CPICH [13].

Feedback of the P-CPICH quality to the BSs is possible, since according to the WCDMA standard, the mobiles periodically report this measure. It is a common rule to allocate 10% of the BS power to the P-CPICH, but from analyzing Fig. 5, it can be seen that for 1FB, 95% of the users have a CIR around -16 dB. Hence less power can be allocated to the P-CPICH without sacrificing the cell coverage. However for 2FB and 4FB the CIR of the P-CPICH is slightly better greater than the desired CIR target. The proposed power tuning algorithm for the P-CPICH is shown in Fig. 5. It is clear that tuning the P-CPICH power ensured that 95% of the users met their P-CPICH quality regardless of the number of beams and traffic in the sector. The impact of the P-CPICH tuning on the system capacity is shown in Table III. Adapting the P-CPICH yields substantial system capacity gain.

B. Impact of Angular Spread

In order to evaluate the impact of AS on the DL system performance, \( \sigma_m \) was set to zero, as a reference case (named "AS0"). The results are summarized in Table IV. The AS induces 7% and 16% relative system throughput loss compared to the AS0 case for 2FB and 4FB per sectors, respectively. Obviously, a narrower beam is more susceptible to the effects of the angular spread. Assuming PB SC allocation and an adequate tuning of the common channel, the relative system throughput gain of 2FB and 4FB is about 1.6 and 2.1 times compared to a 1FB as it shown in Table V.

<table>
<thead>
<tr>
<th>Channel</th>
<th>FB</th>
<th>Relative Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS0</td>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td>TU</td>
<td></td>
<td>0.93</td>
</tr>
<tr>
<td>AS0</td>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td>TU</td>
<td></td>
<td>0.84</td>
</tr>
</tbody>
</table>

TABLE IV
RELATIVE SYSTEM GAIN IN AS0 AND TU, POWER BASED SC ALLOCATION, P-CPICH TUNE ON.

V. IMPACT OF THE ANTENNA SITE CONFIGURATION

The relative gain of 3Sec equipped with 4FB is rather poor. As the number of beams increases then the mismatch between the channel IR from the broad and narrow beams differs substantially due to AS. In order to mitigate some of the losses in the 4FB case, it is suggested to increase the number.
of sectors per site and reduce the number of beams per sector while keeping the product of the two constant (i.e. identical hardware complexity). For instance, an alternative to a 3Sec site equipped with 4FB each is to have a 6Sec site equipped with 2FB each. In Table VI the two site configurations are compared. The 6Sec-2FB case yields 12% and 13% capacity gain for the TU and AS0 radio channel, respectively.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Nb sector</th>
<th>FB per sector</th>
<th>Relative Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS0</td>
<td>3</td>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2</td>
<td>1.12</td>
</tr>
<tr>
<td>TU</td>
<td>3</td>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2</td>
<td>1.12</td>
</tr>
</tbody>
</table>

**TABLE VI**

System gain relative to a single antenna for AS0 and TU, Tune On, Power Based SC allocation.

VI. CONCLUSIONS

The performance of a WCDMA BS equipped with a fixed beam (FB) system using P-CPICH as phase reference is evaluated in dynamic radio network simulator for typical urban radio channel with an accurate intra- and inter-cell interference model. A power based scrambling code (PBSC) allocation method was proposed. In addition, a power tuning algorithm of the P-CPICH that ensures a good CIR quality for 95% of the users, was implemented. Taking into account the PBSC allocation and power tuning of the P-CPICH, the relative gain in a 3-Sec configuration of 2 and 4FB compared to 1FB is around 1.5 and 2.1, respectively. The system degradation due to spatial dispersion of the channel is minor in terms of system capacity for the 2FB case but noticeable, around 16% in the 4FB case.

The relatively low system gain of a 4FB in a 3-sector site is due to the mismatch between the channel IR from the broad and narrow beams that differs substantially with increasing angular spread. Hence leading to erroneous channel estimation. Another antenna site configuration of similar complexity, i.e. 6 sectors site equipped with 2FB each, helped to produce additional 12% system capacity gain. Taking the new configuration into account the 6Sec-2FB system capacity gain will raise up to 2.4 times compared to a 3Sec-1FB system.

REFERENCES


