Enhancements to MIMO Enabled Cells in WCDMA Cellular Systems

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Abstract—**Multiple input multiple output (MIMO) technologies are being introduced in wideband code division multiple access (WCDMA) systems to improve their spectral efficiency. Application of MIMO requires pilot and data signals to be transmitted in the downlink (DL) from each of the two antennas of the base station (BS). At certain time instants, however, single antenna (SA) transmissions may yield instantaneously improved performance compared to MIMO, even though MIMO improves performance at other times. Performance gains of discontinuous secondary pilot transmissions and single antenna transmissions to MIMO MS schemes are investigated by simulation. Practical implementation issues are analyzed to validate deployment feasibility and estimate practical throughput gains compared to the simulation results.**

Keywords – MIMO, reference signals, WCDMA, legacy terminals, HSDPA

I. INTRODUCTION

When a high speed downlink packet access (HSDPA) mobile station (MS) in a typical wideband code division multiple access (WCDMA) cellular system is configured in the multiple input multiple output (MIMO) mode, it is allowed to report to the base station (BS) single stream (SS) or dual stream (DS) channel quality indicators (CQI). The choice between SS and DS CQI depends on the current channel conditions, assuming that the BS can send data from 2 transmitting (TX) antennas and a MS can use 2 receiving (RX) antennas (2x2 MIMO). The MIMO operation in HSDPA systems is well described and investigated in several publications [1][2].

A MIMO capable MS (we will use the term MIMO MS throughout the remainder of this paper) will not consider 1x2 transmission from a single BS antenna. In some scenarios, however, this type of transmission could be beneficial, e.g. in a multi path environment, when the inter stream interference may limit the usage of DS transmission because the power assigned to the two streams is fixed. Another example may be a situation when, in the case of single stream transmission, the power received from the second TX antenna is much lower than from the first one. In these cases, sending data from one antenna only may lead to higher throughput. The presence of MIMO MSs in a cell requires transmitting pilot signals from both TX antennas of the BS for correct MIMO CQI estimation. These pilots are the primary common pilot channel (P-CPICH) and the secondary common pilot channel (S-CPICH) and are constantly transmitted from the primary and the secondary TX antenna of the BS, respectively. During single antenna transmission to a legacy 1x2 single input multiple output (SIMO) MS, the power that the BS spends on S-CPICH reduces the amount of power spent on user data. Furthermore, even for MIMO UEs at certain time instances a situation can arise in which the gain from the MIMO transmission is lower than the overhead for the second pilot.

In this paper, we investigate means of improving a WCDMA cellular system that is configured to operate in the MIMO mode (we will use the term MIMO cells in this paper) to deal with the above issues. We consider single carrier 2x2 MIMO cells and assume that only one HSDPA terminal is scheduled during one transmission time interval (TTI), equal to 2ms. The investigation is focused on a WCDMA cellular system where spreading and direct sequence (DS) scrambling is applied to the transmitted signals. The chip rate is 3.84 mega chips per second. All possible terminal types, i.e. legacy 1x1 or 1x2 SIMO, legacy 2x2 MIMO and a new type of 2x2 MIMO MS supporting the proposed new schemes are considered.

We describe the concept and explain how we model it in a simulation environment in Section 2. Link and system level simulation results are presented and discussed in Section 3. We discuss a number of problem areas associated with practical aspects of implementing the enhancements in real world WCDMA cellular systems in Section 4. We discuss the balance between the gains shown in the simulations and the expected increased system and terminal complexity when deploying the proposed enhancements. Section 5 concludes the paper.

II. CONCEPT AND MODEL DESCRIPTION

In order to improve system performance, we investigate the introduction of two enhancements in MIMO cells: single antenna transmissions towards MIMO terminals and discontinuous S-CPICH transmission. The following subsections describe these two concepts as well as the simulation models used for performance evaluation.

A. Single Antenna Transmissions towards MIMO Terminals

A new pre-coding weight equal to (1, 0) is allowed for SS data transmissions in addition to the already existing four other weights. This means that a BS is able to schedule single antenna transmission to MIMO terminals when the propagation conditions are such that the throughput achieved this way is higher than with a MIMO transmission (either single or dual stream). Only primary antenna transmission, i.e. transmission from the same BS antenna as the one P-CPICH is transmitted from is considered here, whilst maintaining S-CPICH transmission from the secondary antenna. In these cases, the new 2x2 MIMO MS has to be able to report a single TX antenna CQI. This can be by means of always reporting 3 CQI (dual stream, single stream, single antenna) or switching to single antenna reporting when single antenna CQI is higher than dual antenna CQI. A further improvement can be obtained if a BS deactivates the S-CPICH and transfers the power to the user data channel (as described below). This should have the combined benefit of both increasing the power on the user data channel and decreasing intra cell interference from the S-CPICH channel towards user data reception.

B. S-CPICH Discontinuous Transmission

The S-CPICH is not needed for data demodulation when non MIMO terminals are scheduled. To reduce its overhead, the BS scheduler is given the flexibility of dynamically activating/deactivating the S-CPICH in each TTI depending on whether the scheduled MS is a MIMO terminal or not. Thus the BS does not waste power (typically 5-10%) on S-CPICH and instead power can be reallocated to increase user data for the non MIMO terminal. S-CPICH discontinuous transmission (DTX) has a number of consequences:

- Intra cell interference changes by some additional amount due to alternating addition and removal of the secondary pilot, which has impact on the CQI reporting for legacy 1x1 and 1x2 SIMO MSs.
- The channel estimation processes for S-CPICH in 2x2 MIMO terminals are disrupted; hence MIMO MS are likely to send erroneous MIMO CQIs.
- When receiving MIMO data transmissions, demodulation performance of MIMO MS could be affected by a lack of S-CPICH in prior slots.

Thus, for the S-CPICH deactivation to work effectively in a real system, certain prerequisites are necessary:

- Enabling 2x2 MIMO MS to know explicitly or estimate where S-CPICH is not transmitted in order to avoid corruption of their channel estimation filters.
- Deploying a mechanism in the BS to estimate and correct CQI reports (the BS is aware of when the S-CPICH was not transmitted) from non MIMO UEs.
- Reactivating S-CPICH transmission at the base station prior to scheduling a MIMO terminal for the sake of correct MIMO CQI reporting.

It should be noted that in the simulations, these real implementation constraints are not taken into account, but rather ideal CQI reporting is assumed. Thus, the simulation results represent best case estimates for the gain.

C. Link Level Simulations

The aim of the link level simulations described in this section is to quantify the benefits of single antenna transmission towards MIMO MS, as described in section A. Estimation of post-receiver signal-to-interference-and-noise-ratio (SINR) for three different transmission schemes (1x2, single-stream and dual-stream) in each TTI is performed (the SINR estimation methodology is described in [3]). This estimation is done after determining pre-coding weights which assure the highest SINR on the primary stream in the case of MIMO transmission. SINR values are mapped to throughput C using the following modified Shannon formulation:

$$C = 0.75 * 3840000 * \log_2(1 + SINR) \tag{1}$$

The highest value from the set below is then chosen and the corresponding transmission scheme is recommended to the BS to use 3 TTI later (this is equivalent to CQI reporting):

- Throughput obtainable with single antenna (SA) 1x2 SIMO transmission.
- Throughput achievable with single stream 2x2 MIMO transmission.
- Sum of throughputs obtainable with dual stream 2x2 MIMO transmission (primary and secondary stream).

In each TTI, the SINR corresponding to actual data transmission is then recorded, which serves as a measurement to quantify the gains of employing SA transmission and S-CPICH DTX. Ideal channel knowledge at the receiver is assumed.

The following simulation scenarios have been evaluated:

- Baseline case – where only dual antenna single stream and dual stream transmissions are possible. In this case, the fallback to SA transmission is not allowed. The power allocation is kept constant during the simulation and powers of both pilots are equal 10% of the total BS transmit (TX) power each.
- Test case 1 – where single stream and dual stream MIMO and single antenna transmission is allowed. The power allocation is not changed during the simulation, and, as in the baseline case, there is no power imbalance between pilots. The scope of this test case is to quantify the gains of introducing an additional transmission scheme and to check the percentage of fallbacks to single antenna transmission. In the following part of the paper, we refer to this test case as MIMO+SA.
- Test case 2 – single and dual stream MIMO and SA transmission allowed. During MIMO transmission, the powers of primary and secondary pilot are equal, but for the time of 1x2 transmissions, the S-CPICH is deactivated. Power allocated to this channel is used as an additional grant for user data transmission. Virtual Antenna Mapping (VAM) is used, i.e. a fixed pre-coding weight vector with all channels using it is applied to distribute signals from virtual to physical antennas. Power not allocated to one virtual antenna branch can be re-allocated to the other physical antenna (an example implementation of power balancing between the antennas can be found in [4].) The aim of this test case is to quantify the gains of deactivating the secondary pilot, which leads to lowering the interference and increasing the data channel power. When referring to this test case, we use MIMO+SA+DTX.

- Test case 3 – MIMO transmissions in all TTIs. In this test case, pilot power imbalance is envisaged. Secondary pilot has 3dB less power than the primary; however during the simulation this ratio is not changed. This test case can be seen as baseline for test case 4 and is referred to as MIMO UNBAL.
- Test case 4 – MIMO and SA transmissions allowed, 3 dB power imbalance between pilots, S-CPICH deactivation during 1x2 transmissions. VAM is applied. The aim is to check the gains of combined S-CPICH DTX and pilot power imbalance. This test case is referred to as ALL UNBAL.

The table below summarizes the simulation environment settings. We use the following symbols to express the power relationships between different channels:

- Ec – per chip energy of the channel of interest,
- Ior – average energy per chip at the transmitter,
- Ioc – total power of interference from other sites seen at the MS RX antenna,
- Îor – this corresponds to the total power from the own BS seen at the MS RX antenna,
- Îor/Ioc – geometry.

TABLE I. LINK LEVEL SIMULATION ASSUMPTIONS

Parameter	Value
Fast fading channel	Pedestrian A (PA, 3km/h) Vehicular A (VA, 3km/h, 120km/h)
Delay between decision on which transmission scheme to use and SINR calculation	9 slots (three slots contribute to one TTI)
P-CPICH Ec/Ior	-10dB
S-CPICH Ec/Ior	-10dB when present (baseline, MIMO+SA and MIMO+SA+DTX) -13dB when present (MIMO UNBAL and ALL UNBAL)
Ec/Ior on other control channels	-7dB
Ec/Ior on user data channel	-2.2dB when S-CPICH present (baseline, MIMO+SA and MIMO+SA+DTX) -1.87dB when S-CPICH present (MIMO UNBAL and ALL UNBAL) -1.55dB when S-CPICH not present
Îor/Ioc	-3dB (low geometry), 15dB (high geometry)

D. System Level Simulations

The system level simulations record the throughput increase when implementing the S-CPICH DTX scheme described in section B; i.e. when transmitting to a mix of 1x2 SIMO MS and 2x2 MIMO MSs under idealized conditions. A fixed number of sixteen MS per cell is assumed. The proportion of 1x2 SIMO to 2x2 MIMO MS is varied. The simulations investigate SS-only MIMO as well as SS/DS MIMO (with rank switching) with proportionally fair (PF) scheduling. A full buffer traffic model is assumed, i.e. all users always have something to receive in every TTI. Either 10% or 5% of total BS power (20W) is allocated to S-CPICH. During transmissions to 2x2 MIMO users, on virtual antenna 1, 2W are assigned to P-CPICH, 2W for other control channels, and 7W (8W with 5% S-CPICH power mapping) to user data transmission and, on virtual antenna 2, 2W (1W with 5% S-CPICH) are assigned to S-CPICH and 7W to user data. With baseline simulations, during transmission to 1x2 SIMO MS most of the power is on virtual antenna 1 (14W or 15W with 5% S-CPICH for user data, 2W for other control and 2W P-CPICH) and 2W (1W with 5% S-CPICH power mapping) is applied to virtual antenna 2. When applying S-CPICH DTX, during transmission to 1x2 SIMO users all power (16W on user data, 2W on other control and 2W on P-CPICH) is applied to virtual antenna 1 while no power goes to virtual antenna 2. After VAM power balancing, 10W are transmitted from each of the two physical antennas in all cases.

III. SIMULATION RESULTS

A. Link Level Simulations

In Figure 1 and 2, mean throughput gains from test cases 1-4 can be seen relative to the baseline case. Additionally, ALL UNBAL mean throughputs are compared to those of MIMO UNBAL in Figure 3.

The gains of MIMO+SA come from the introduction of the third possible transmission scheme that can be regarded as additional pre-coding weight for SS transmissions. They vary from 3% to 12%. The highest gains can be seen in high geometry, but not for all types of channel. With the PA channel, the gain is close to 5%.

MIMO+SA+DTX shows gains from 6% up to almost 25%. The reason for that is a combination of additional transmission scheme, higher data channel power in case of single antenna transmission, VAM application, and decrease of interference level due to S-CPICH DTX.

In the test case MIMO UNBAL that serves as base line for ALL UNBAL, the source of the gains is the power allocation – more power is mapped to the user data channel and less power for S-CPICH, which leads to lower interference. The allocation to user data is increased from 0.6 to 0.65 of the total BS power, which means that the power of the data channel is increased by 8.3%. Gains of this test case vary from 7 to 10%.

The test case ALL UNBAL typically led to the highest gains relative to the baseline (between 12% and 27%). However, the gains of this scheme are within the range of 3% and 16% when MIMO UNBAL becomes the baseline. The reasons for the gains are similar to the ones of MIMO+SA+DTX.

The results are promising, however they only indicate an upper-bound of gains achievable with single antenna transmission due to applying idealized conditions in the simulations (perfect channel knowledge in the BS and MS).

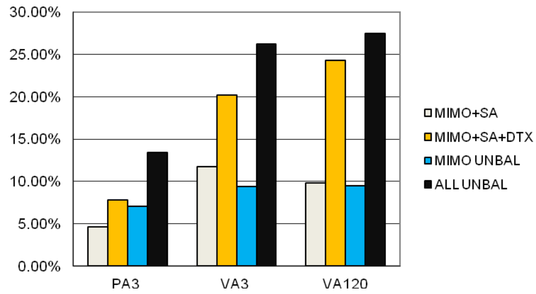

Figure 1. Mean throughput gains over baseline – low geometry MS

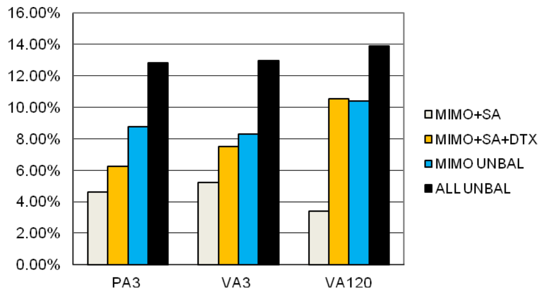

Figure 2. Mean throughput gains over baseline – high geometry MS

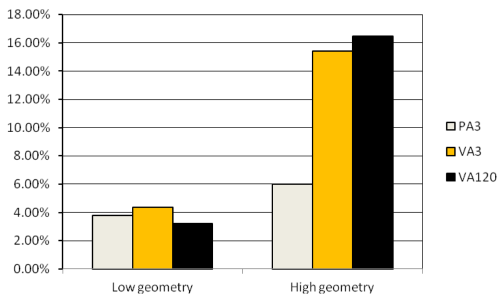

Figure 3. Mean throughput gains of the ALL UNBAL scheme over MIMO UNBAL

B. *System Level Simulations*

As with the link level study, the system level simulations were performed assuming ideal channel knowledge. S-CPICH power assignment was equal to 10% and 5% but only results corresponding to the 10% setting are shown. Simulations were performed for the baseline MIMO and S-CPICH DTX schemes. The results for the PA channel model are shown in Figure 4. The throughput increase versus the number of 2x2 MIMO MS is shown in Figure 5, where the maximum increase of 14% can be seen. When the VA channel model is used, the maximum average throughput increase (of the S-CPICH DTX scheme over baseline) rises from 14% to 21% (Figure 6 and 7). The gains of the S-CPICH DTX scheme are very low in either type of channel when the number of 2x2 MIMO MS is high. This is due to the fact that S-CPICH cannot be switched off very often. For 5% S-CPICH power allocation, the average throughput increase reduces to only 7% with the PA and 12% with the VA channel.

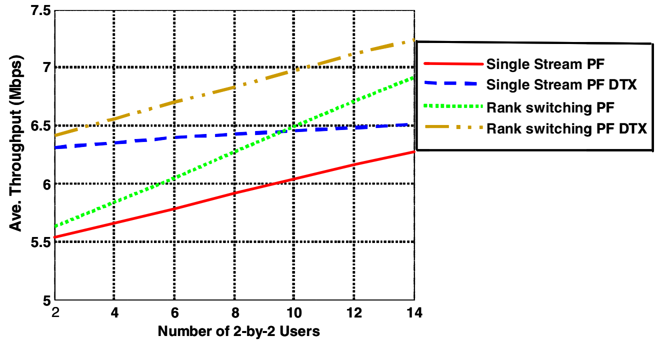

Figure 4. PA, average cell throughput (Mbps) versus the number of 2x2 MIMO users (10% S-CPICH)

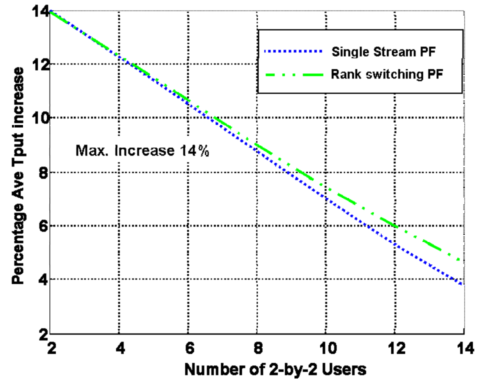

Figure 5. PA, Percentage average throughput increase versus the number of 2x2 MIMO users (10% S-CPICH)

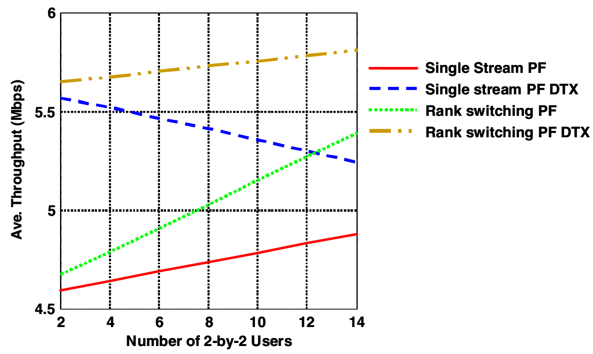

Figure 6. VA, average cell throughput (Mbps) versus the number of 2x2 MIMO users (10% S-CPICH)

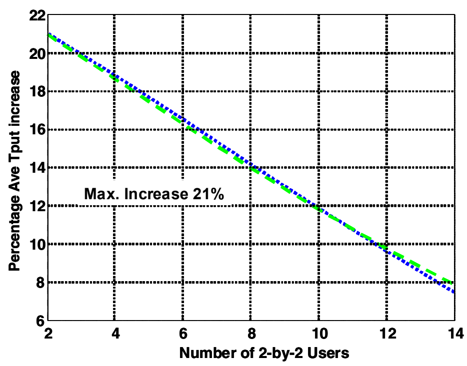

Figure 7. VA, percentage average throughput increase versus the number of 2x2 MIMO users (10% S-CPICH)

IV. DISCUSSION OF SYSTEM IMPLEMENTATION

In order for the investigated concepts of single antenna transmission towards MIMO MS and/or discontinuous S-CPICH transmission to be attractive for network evolution, ideally, the following criteria should be satisfied:

1) No changes in the system infrastructure nor hardware modifications in the network elements are required.

2) Significant gains are achievable with new terminals, i.e. those capable of operating in both 2x2 MIMO or 1x2 SIMO modes

3) System performance for legacy 1x1, 1x2 SIMO and legacy 2x2 MIMO terminals is not penalized (operation for legacy terminals is described in [5].)

It seems that it is not necessary to modify infrastructure nor hardware of the base stations when implementing the considered proposals. Simulation results presented in Section 3 promise clear gains in terms of achievable throughput both on individual link and whole system level when assuming perfect channel knowledge in the BS and MS. The simulations show that noticeable performance improvement in the range from 10% to 20% is only possible when implementing single antenna transmissions to MIMO MS along with S-CPICH DTX. However, with the modifications to pilot transmission discussed in this paper, the process to acquire knowledge of the current channel characteristics will become more complex.

A. Performance of New 2x2 MIMO MS with Practical S-CPICH DTX Implementation

Since S-CPICH transmission is proposed to be discontinuous, the activity pattern needs to be known to new 2x2 MIMO terminals for correct CQI estimation. A sensible way to achieve this is to make it periodic so that the new MS can repeatedly estimate MIMO CQI at explicitly defined time instants, signalled by the network, and non MIMO CQI, i.e. 1x2 single antenna CQI, when S-CPICH transmission is not due within its activity cycle in the cell. In this way all types of CQI can be made available at the BS scheduler. As a consequence of periodic S-CPICH transmissions, MIMO CQI has to be reported simultaneously from all new type MIMO terminals at specific time intervals and single antenna ones at others which may lead to high instantaneous load on the uplink control channel (UL HS-DPCCH). Loss of CQI accuracy is another issue do to increased latency for a fixed reporting rate. Additionally, allowing single antenna transmissions towards new MIMO MS leads to increased vulnerability of MIMO CQI reports since the channel coding applied on them has to allow for choosing between three types of recommendation instead of two as with the old type of MIMO CQI: between dual stream dual antenna, single stream dual antenna and single antenna transmission. Ideally, MIMO data transmissions can be scheduled in line with the periodic S-CPICH activity pattern and single antenna transmissions outside it. Practically, this cannot be guaranteed and S-CPICH has to be switched on whenever a MIMO transmission is to occur and this impairs single antenna CQI estimations as the new MIMO terminals cannot be aware of that. The duration of each S-CPICH transmission has to be arbitrarily set at the network level and may not be adequate for every terminal's channel impulse response estimation window since the MS implementation is manufacturer specific. The implementation freedom for terminals creates a problem when implementing in the BS mechanisms for correcting received CQI impaired by lack of complete terminal awareness of all S-CPICH transmissions.

B. Performance of Legacy Terminals

Legacy MIMO terminals cannot be aware of S-CPICH discontinuous transmission and they will deliver to the BS erroneous MIMO CQI recommendations with poor transmission schemes when CQI is measured during periods of S-CPICH DTX. The base station will only be able to rely on CQI reports that are known to have been made when the S-CPICH was active; however this knowledge cannot be exact. For 1x1 and 1x2 SIMO MS, discontinuous S-CPICH transmission introduces small interference variations, which renders CQI reporting more difficult. BS implementation to correct such CQI reports can be difficult due to reasons discussed above.

V. CONCLUSION

We investigated proposals to improve the capacity of MIMO cells in WCDMA mobile systems: enabling single antenna transmission towards MIMO terminals, discontinuous presence and power reduction of the secondary pilot. Simulations indicated clear throughput gains are achievable, especially for high geometry MS in Vehicular A channels. However, when the penetration of new type 2x2 MIMO MS is low, there is no longer much throughput gain in the system. Moreover, the idealized conditions assumed in the simulations are difficult to meet in practice as there are problems with proper channel state knowledge at the BS transmitter and MS receiver when discontinuously sending pilot from the secondary BS antenna. Despite this, the concepts presented in this paper can prove much more beneficial with the expected introduction of 4 transmit antenna schemes to WCDMA HSDPA systems where four pilot channels instead of two will be required.

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