Simultaneous 5GHz Co-channel MIMO Links at Microcellular Boundaries: Interference or Cooperation?

Tim W C Brown, MIET, Aalborg University, Denmark (Now with University of Surrey, UK)

Patrick C F Eggers, Aalborg University, Denmark

Kim Olesen, Aalborg University, Denmark

Abstract - Simultaneous real time 4x4 MIMO measurements from three base stations to the same mobile are analysed. Such measurements can be applied to determine the real time scale of interference from neighbouring cells due to lack of orthogonality between their respective eigenvectors. This paper also compares new and existing schemes that can be applied in equally valid ways to suppress or take advantage of the unwanted base station links at cellular boundaries, thus it opens up the possibility of either interference or cooperation on a microcellular boundary.

Index Terms: Eigenvalues, Eigenvectors, Interference, Cooperation

1. Introduction

Multiple input multiple output (MIMO) concepts are considered as one of the key methods for the current and next generation of mobile radio as a means to increase capacity and spectral efficiency of mobile links [1][2][3]. Co-channel interference, however, is one of the key factors which degrades the performance when at the cellular boundary or in comparable proximity to neighbouring base stations. Several publications have already shown various models and measurement results with regards to a single base station with multiple antenna elements at both ends [4] though neighbouring co-channel links would be in existence. Few measurements have been undertaken with a focus on MIMO channels with interference included [5] and none that the authors are aware of with regards to simultaneous real time measurements, only in the case of multiple antenna links for wideband code division multiple access (WCDMA) applications [6]. This paper therefore aims to quantify the scale of interference generated by the neighbouring co-channels and then considers how to either suppress the interference or use it in cooperation [7].

The first three sections of this paper present the background theory, measurement overview and also the initial results of interference between base station links. The final section then has subsections that consider how interfering base stations can be suppressed or cooperated with to improve capacity. Integrating the base station links to create 8x4 and 12x4 links is first considered, though this adds costly complexity in resolving eigenmodes. Simpler schemes applying optimum combining to receive three simultaneous SISO links are also

considered where capacity potential is compared. Finally two 4x2 MIMO links are considered where the two extra branches at the mobile can either suppress interference or facilitate cooperation.

2. Background Theory on Eigenmode Analysis

The analysis of the singular values, $\mathbf{S}$, and eigenvectors, $\mathbf{U}$ and $\mathbf{V}$ at the mobile and base station respectively, can be determined by the singular value decomposition (SVD) of the channel in the 4x4 case, $\mathbf{H}$ [8]:

$$\mathbf{H} = \mathbf{U} \mathbf{S} \mathbf{V}^H = \begin{bmatrix} \mathbf{u}_1 & \mathbf{u}_2 & \mathbf{u}_3 & \mathbf{u}_4 \end{bmatrix} \begin{pmatrix} s_1 & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & 0 \\ 0 & 0 & 0 & s_4 \end{pmatrix} \begin{bmatrix} \mathbf{v}_1^H & \mathbf{v}_2^H & \mathbf{v}_3^H & \mathbf{v}_4^H \end{bmatrix} \quad (1)$$

where there are 3 separate 4x4 MIMO links for each BS, $\mathbf{H}_A$, $\mathbf{H}_B$ and $\mathbf{H}_C$, which can each be decomposed to respective eigenvectors and singular values (four in each case) also labelled with A, B and C as appropriate. The measured instantaneous random fading on the three sets of four singular values and eigenvectors opens many avenues for further analysis. An important matter with regards to interference of base stations is the orthogonality between the eigenvectors, which ideally should be zero and in the worst case unity, defined as follows:

$$\text{Between base station A and B} \quad \mathbf{U}_A^H(n) \mathbf{U}_B(n) \quad \mathbf{V}_A^H(n) \mathbf{V}_B(n) \quad (2)$$

$$\text{Between base station A and C} \quad \mathbf{U}_A^H(n) \mathbf{U}_C(n) \quad \mathbf{V}_A^H(n) \mathbf{V}_C(n) \quad (3)$$

$$\text{Between base station B and C} \quad \mathbf{U}_B^H(n) \mathbf{U}_C(n) \quad \mathbf{V}_B^H(n) \mathbf{V}_C(n) \quad (4)$$

where the diagonal elements of the inner product will give the level of orthogonality of the four eigenvectors in each case. The total signal to interference ratio (SIR) of the first eigenmode can also be evaluated so for example, the SIR for the wanted BS_A due to the interference of BS_B at a cell boundary is defined:

$$\text{SIR}_{A/B} = \frac{s_{1A}^2(t)}{\left| \mathbf{u}_{1A}^*(t) \mathbf{H}_B(t) \mathbf{v}_{1B}(t) \right|^2} \quad (5)$$

where including BS_C will contribute even further interference.

3. Measurement Campaign Setup

The measurement setup used three separate 4 element base stations with directional antennas facing the direction of the mobile appropriately positioned to give a similar link budget between 3 base stations so there is a 1:1 cell re-use scenario applied. Each base station is on a rooftop outdoor location and as can be seen in Figure 1, base station BS_A (photographed in Figure 3 (b)) is located in the same position for the two configurations, “star” (within the triangular box) and inline (within the rectangular box). Antennas BS_B and BS_C are appropriately positioned for the two configurations, which reflect scenarios at a cell intersection or long range interference respectively. The mobile, MS, was placed indoors with a glass roof as illustrated in Figure 3 (a) to provide a semi line of sight (SLOS) scenario.

Figure 1 - Plan of two BS configurations of “star” in the triangle box and inline in the rectangle box

Two designs of handset were used and measurements were repeated with several different users to account for any differences. Each measurement was undertaken with two users at a time, each using one of the mobile handsets illustrated in Figure 2. Direct cables were connected to the handsets, which at 5GHz have negligible effects due to the small wavelength compared to the mobile terminal size [10]. Measurements were sampled at a rate of 60Hz, roughly three times the Doppler frequency for 5GHz walking at a speed of 4km/h.

Figure 2 - Two designs of mobile handsets used with printed monopoles

Figure 3 - Measurement campaign run (a) at the mobile indoors and (b) from the base station to the building

Figure 4 shows the channel sounder arrangement where the channel impulse response was measured as described in [11]. Each base station transmits a random PN sequence with synchronised correlated channel impulse responses via a power amplifier to each of its 4 Tx antennas. At the receiver, two 4 branch mobiles are measured simultaneously by the automatic gain control (AGC) where data to be calibrated later on can be recorded by the analogue to digital converter (ADC) and a personal computer (PC). Before measurement, it is necessary to synchronise the time delay for each of the transmit signals so that they would be received within the appropriate time slots by the receiver, thus enabling continuous measurement of both sets of 48 channels. The wideband channel data was filtered down to narrowband in post processing by considering the fading signals of only the centre frequency.

Figure 4 - Channel sounder architectures at both the three base stations and mobile

4. Analysis of Orthogonality and Interference

The orthogonality of the eigenvectors was first evaluated to determine their ability to ignore unwanted signals from the interfering base station. One example for the inline configuration shows plots of $\mathbf{u}_{1A}^H \mathbf{u}_{1B}$, $\mathbf{u}_{1A}^H \mathbf{u}_{1C}$ and $\mathbf{u}_{1B}^H \mathbf{u}_{1C}$ in Figure 5, where results are comparable for all other eigenmodes - $\mathbf{u}_{nA}^H \mathbf{u}_{nB}$, $\mathbf{u}_{nA}^H \mathbf{u}_{nC}$ and $\mathbf{u}_{nB}^H \mathbf{u}_{nC}$. The unit dBVec is also applied where it is taken as $20\text{Log}()$ of the linear value so $-\infty\text{dBVec}$ would give true orthogonality. The results however show a median value of around -7dBVec occurs in all cases, both for inline and “star” configurations. The average values for all users are even worse, not getting lower than -2dBVec as shown in Table 1, which is not at all sufficient for self suppression of interference at the mobile.

Figure 5 - Cumulative distribution plot of the orthogonality of the $\mathbf{u}_1$ eigenvector when two base station links are compared, AB, AC and BC, with different users applied

$\mathbf{u}_{1A}^H \mathbf{u}_{1B} / \text{dBVec}$	$\mathbf{u}_{1A}^H \mathbf{u}_{1C} / \text{dBVec}$	$\mathbf{u}_{1B}^H \mathbf{u}_{1C} / \text{dBVec}$
-1.38	-0.97	-1.51

Table 1 - Comparison of the average orthogonality between three base station links from the same mobile defined in dBVec
Taking the results in Figure 5 further to consider the SIR, these results are presented in Figure 6 (a), which applies equation (5) to evaluate SIR A/B in the inline configuration as a typical example. As can be seen the SIR is below 10dB around 80% of the time which is not sufficiently low interference. Figure 6 (b) also considers the SIR when both interference from base stations B and C are included, which reduces even further due to the increase in interference, generally less than 3dB more than 80% of the time. Other eigenmodes from the interfering base stations will add further interference, though this is not worth investigating when they will make no improvement. Table 2 shows the average signal to noise ratios for all users plotted in Figure 6 as well

as the standard deviation. The average values are not significantly high at 13dB for just one interferer and down to 7dB for two interferers, with also low median values as identified in Figure 6.

Figure 6 - Cumulative distribution plot of the signal to interference ratio of the first eigenmode between (a) base stations A vs B and (b) base stations A vs (B and C) for the inline configuration

	SIR (A vs B) (dB)	SIR (A vs (B+C)) (dB)
Average	13.50	7.69

Table 2 - Diagram showing a comparison of average and standard deviations of the mean signal to interference ratio for all users

For the purpose of using the base station links for later analysis, the correlation between the eigenvalues should be low. As an example, Table 3 shows the average correlation between different base station links for all four eigenvalues when different users are applied. In all cases, the correlation is low, always below 0.3 in given measurements, which can be assumed negligible [9]. Results are much the same in the case of the “star” configuration.

Eigenvalue	ρ_{AB}	ρ_{AC}	ρ_{BC}
1	0.18	0.23	0.11
2	0.11	0.10	0.13
3	0.18	0.08	0.09
4	0.05	0.06	0.05

Table 3 - Evaluation of the average eigenvalue correlation between base station links A to B, A to C and B to C for the inline configuration

5. Comparison of Link Quality between Base Stations.

To consider how two or three base stations could be used cooperatively, comparing their capacity potential will be of benefit. Correlation between eigenvalues is one aspect of this that has already been considered. Another useful measure for this analysis is to compare the scattering richness between links, since this will not only consider the ratios of the average eigenvalues but also the level of scattering in the different environments. The richness, $R(n)$ is derived in [12], which is a measure of scattering in a mobile environment:

$$R(n) = \sum_{j=1}^n \log_2 \overline{s_j^2} \quad (6)$$

where $\overline{s_j^2}$ is the mean of an eigenvalue numbered by j and n is the “richness order”, which in this case has a maximum of 4. Closer eigenvalues will allow a greater deal of richness, which will in turn allow $R(n)$ to increase with n , rather than reach a peak value when n is less than 4. Low Richness (i.e. a high Rice factor) will always have $R(1)$ as the highest and thereafter decreasing. As illustrated in Figure 7, the four scatter plots (one for every n) have three scatter comparisons on each plot, which are as follows:

- $R(n)_A$ with $R(n)_B$;
- $R(n)_A$ with $R(n)_C$;
- and $R(n)_B$ with $R(n)_C$

where different users are applied for each scatter point of which there are 20 using the inline BS configuration, giving 60 points on each plot. If all three base station links have comparable scattering richness, then there should be a good correlation with a positive line of scatter points on all four diagrams. This is seen to be the case for all four values of $R(n)$, where also later on Figure 8 shows there are comparable richness curves between all base station links for an example case. Thus there is comparable capacity potential in all three links.

Figure 7 - Scatter comparison of the richness between three 4x4 base station links, A B and C for the inline configuration with different users measured each time

6. Discussion of Possible Techniques for Cooperation between Base Station Links

A good orthogonality between the MIMO links would allow a switched diversity to be applied at the mobile, so that the fading on each of the 4 eigenvalues could be reduced (since they are decorrelated) and this would create a more constant capacity. Unfortunately this is not the case, so it is necessary to consider how post processing can be applied at the mobile to suppress unwanted interferers or take advantage of them, which the following subsections will consider.

6.1. Integrated 8x4 and 12x4 MIMO links

Adding a second and even third base station link to create an integrated 8x4 or 12x4 link will allow increased overall richness, provided that all three BS links have a good and comparable richness, which has been analysed

in Figure 7. Figure 8 compares the richness curves taking the average $R(n)$ for each of the single links and the combined links for the inline configuration. There is comparable average richness for two combined 8x4 BS links, BS_A/BS_B and BS_A/BS_C and when all three are combined, there is significant gain in richness. This gain in richness is observed by the fact that the third order richness for individual BS links is lower than the second order richness, however this is not the case with two or three integrated base stations, which are causing a global “cross BS link” increased scattering and thus taking advantage of separate BS links. It is assumed, however, that the path loss is equalised between all BS links. Further to this, there is complexity in performing the SVD where all three base stations will need to communicate with each other in order to resolve the eigenmodes from the channel state information. Consideration of other possibilities will therefore enable more efficient use of the BS links. Similar results also occur for the “star” configured measurements. From this point onwards only the inline configuration data is analysed for clarity because similar results were found to be the case with the “star” configuration. The point in comparing the “star” and inline configurations (which are two valid cases for positions of interfering base stations on a cellular boundary) verifies that there are similar characteristics involved independent of where the base stations are positioned. It is possible that path length can impact the scattering richness, which was not found to be significant in the cell boundary scenario due to the scattering scenario analysed.

Figure 8 - Comparison of the richness curves between individual 4x4 base station links as well as combined 8x4 and 12x4 links

6.2. Post Processing Techniques for Cooperation and Interference Suppression

A simpler approach to consider for cooperation between base stations is to apply an optimum combining weight, $\mathbf{w}_s$, illustrated in Figure 9, where there are selected BS weightings, $\mathbf{w}_A$, $\mathbf{w}_B$ and $\mathbf{w}_C$ so that three separate cooperative SISO links, $\mathbf{h}_1$, $\mathbf{h}_2$ and $\mathbf{h}_3$ arrive at the mobile. This avoids the need for base stations to communicate with each other as the mobile has control over the individual links.

Figure 9 - Illustration of the transmission of the first eigenmode from wanted and interfering base stations

The links, $\mathbf{h}_1$, $\mathbf{h}_2$ and $\mathbf{h}_3$, can be resolved using the weights when the physical channel links, $\mathbf{H}_A$, $\mathbf{H}_B$ and $\mathbf{H}_C$ are known:

$$\mathbf{h}_1 = \mathbf{H}_A \mathbf{w}_A \quad \mathbf{h}_2 = \mathbf{H}_B \mathbf{w}_B \quad \mathbf{h}_3 = \mathbf{H}_C \mathbf{w}_C \quad (7) \quad (8) \quad (9)$$

If $\mathbf{h}_1$ is arbitrarily chosen as the wanted channel, then the optimum weight can be resolved using the correlation matrix, $\mathbf{R}$, to perform the well known method of optimum combining, provided the links are de-correlated [13]:

$$\mathbf{w}_s = \mathbf{R}^{-1} \mathbf{h}_1 \quad (10)$$

where:

$$\mathbf{R} = \mathbf{h}_1 \mathbf{h}_1^H + \mathbf{h}_2 \mathbf{h}_2^H + \mathbf{h}_3 \mathbf{h}_3^H + P_N \mathbf{I} \quad (11)$$

where P_N is the noise floor power level dependent on the signal to noise ratio (SNR) of the antenna elements. The same routine could be applied to $\mathbf{h}_2$ or $\mathbf{h}_3$ in order to switch between the three base stations. The resultant SIR between base station A and (B and C) for example will then be:

$$\text{SIR A/(B+C)} = \frac{\mathbf{w}_s^H \mathbf{h}_1 \mathbf{h}_1^H \mathbf{w}_s}{\mathbf{w}_s^H (\mathbf{h}_2 \mathbf{h}_2^H + \mathbf{h}_3 \mathbf{h}_3^H) \mathbf{w}_s} \quad (12)$$

Assuming that the base stations themselves are not interfering with each other (since they are spaced with suitable reuse distance) this gives flexibility to apply different weightings at the BS and then optimise at the MS to distinguish the different links. Three weighting schemes are compared in this paper as follows that can distinguish between three BS paths (some of which are considered in [15]):

- **Fixed Weighting** - To simply apply fixed zero phase weights at the base stations all equal to $(\frac{1}{2} \frac{1}{2} \frac{1}{2})^T$. This is simple, though it will cause energy to be lost by radiating in one random direction so it is inefficient.
- **SVD Optimised** - To apply the 4x4 SVD weights for the first eigenmode, $\mathbf{v}_{1A}$, $\mathbf{v}_{1B}$ and $\mathbf{v}_{1C}$ at their respective base stations, which may allow a more optimum link to the mobile. However, this requires more complexity in resolving the SVD from each BS.
- **Time Reversal Optimised** - Using the time reversal concept [14], where the link from one BS to one branch of the mobile is optimised to provide “channel hardening” and the same is done for the other two BS links at two different branches at the mobile. This could therefore increase the strength of the whole channel, where the weights are equal to the normalised conjugate of a matrix row from $\mathbf{H}_A$, $\mathbf{H}_B$ and $\mathbf{H}_C$.

In order to compare the three schemes, it is necessary to first define a reference noise floor, which has been chosen using the fixed mode. When the fixed weights are applied at the BS, the received noise level is calculated using the set reference SNR from the maximum branch at the mobile. Therefore the noise power, P_N , is defined as:

$$P_N = \frac{\max(\overline{|\mathbf{h}_1|^2})}{\text{SNR}} \quad (13)$$

where $\overline{|\mathbf{h}_1|^2}$ returns the average branch power in each of the four branches received at the mobile. The same can be done for $\mathbf{h}_2$ and $\mathbf{h}_3$ so that these noise levels are then applied to evaluate all schemes to see if optimising the weights at the BS will improve the output SIR. Table 4 compares the average SIR produced for an example user. In the first column, the original SIR is shown so that with all three schemes (which all have a common noise floor), it can be seen that there is significant gain in average SIR of at least 30dB. For all three schemes the results have been shown for SNRs of 10dB and 15dB. Applying the SVD optimization or time reversal optimisation does improve the SIR by around 13dB and 16dB respectively. However, that comes at a cost of increased complexity. Though all three cases give significant gain in SIR compared to an interfered mobile,

they do have a contrast in capacity potential as is seen in Table 5. For the fixed weighting, there is a slight degradation in capacity compared to a 4x4 MIMO channel without interference. However, a slight increase in SNR up to about 15dB does improve this to gain comparable capacity. SVD optimised and time reversal optimised links would not require as much increase in SNR as seen by the results in Table 5 though they will increase the level of complexity in the system. Therefore the three schemes presented here provide three examples of how to cooperatively use three base station links with a trade off between complexity and demand for more SNR. The capacity of the cooperative link in these tables is calculated using the signal to interference and noise ratio (SINR) from the three links:

$$C = \sum_{n=A,B,C} \log_2(1 + \text{SINR}_n) \quad (14)$$

The 4x4 link is calculated using the Shannon capacity [8]:

$$C = \log_2 \left| \mathbf{I} + \text{SNR} \cdot \mathbf{S}_A \mathbf{S}_A^T \right| \quad (15)$$

	Standard SIR/ dB	Fixed Tx SNR = 10dB/ dB	Fixed Tx SNR = 15dB/ dB	SVD Optimised Tx, SNR = 10dB/ dB	SVD Optimised Tx, SNR = 15dB/ dB	Time Reversal Optimised Tx, SNR = 10dB/ dB	Time Reversal Optimised Tx, SNR = 15dB/ dB
Mean	8.73	48.31	67.39	61.11	80.68	66.91	86.53

Table 4 – Comparison of the resultant average SIRs, with the original mean SIR in the first column for a single user applying the three proposed schemes for interference mitigation or cooperative useage

	Standard 4x4 Capacity/ b/s/Hz	Fixed Tx SNR = 10dB/ b/s/Hz	Fixed Tx SNR = 15dB/ b/s/Hz	SVD Optimised Tx, SNR = 10dB/ b/s/Hz	SVD Optimised Tx, SNR = 15dB/ b/s/Hz	Time Reversal Optimised Tx, SNR = 10dB/ b/s/Hz	Time Reversal Optimised Tx, SNR = 15dB/ b/s/Hz
Mean	16.79	9.91	13.93	12.67	17.09	13.99	18.63

Table 5 - Comparison of the resultant average capacities, with the original mean capacity in the first column for a single user applying the three proposed schemes for interference mitigation or cooperative useage

6.3. Dual Hybrid 4x2 Links

The final approach is to consider making a 4x2 link to the mobile and using the other two branches as interference suppressors from another 4x2 link. This is illustrated in Figure 10 where 4 branches are required at the mobile to create these dual 4x2 links. If the two eigenmodes of both BS links are known, it is then possible to resolve $\mathbf{w}_s$ at the mobile so that the four separate eigenmodes can be distinguished. Therefore in this case $\mathbf{R}$ is defined as:

$$\mathbf{R} = \mathbf{h}_{p1}\mathbf{h}_{p1}^H + \mathbf{h}_{p2}\mathbf{h}_{p2}^H + \mathbf{h}_{p3}\mathbf{h}_{p3}^H + \mathbf{h}_{p4}\mathbf{h}_{p4}^H + P_N \mathbf{I} \quad (16)$$

where $\mathbf{h}_{pn}$ are resolved channel links taking the strongest two branches at the mobile of $\mathbf{H}_A$ and $\mathbf{H}_B$, which will have the notation $\mathbf{H}_{pA}$ and $\mathbf{H}_{pB}$ (both as 4x2 matrices) so therefore:

$$\mathbf{h}_{p1} = \mathbf{H}_{pA} \mathbf{v}_{p1A} \quad \mathbf{h}_{p2} = \mathbf{H}_{pA} \mathbf{v}_{p2A} \quad \mathbf{h}_{p3} = \mathbf{H}_{pB} \mathbf{v}_{p1B} \quad \mathbf{h}_{p4} = \mathbf{H}_{pB} \mathbf{v}_{p2B} \quad (17)$$

where the vector weights, $\mathbf{v}_{pnA}$ and $\mathbf{v}_{pnB}$ at BSA and BSB respectively are resolved by the SVD of $\mathbf{H}_{pA}$ and $\mathbf{H}_{pB}$. The optimum combining can be applied as before from which the capacity of the two established 4x2 links can be evaluated.

Figure 10 - Illustration of the 4x2 Hybrid Link

The capacity can be compared in two ways. The first is illustrated in Table 6 (a) where the capacity of a non interfered 4x2 MIMO link (with a fixed SNR of 10dB) is compared with the interference suppressed link so that capacity is derived by the SINR of two wanted links, SINR_{p1} and SINR_{p2} :

$$C = \sum_{n=1,2} \log_2(1 + \text{SINR}_{pn}) \quad (18)$$

Thus in this situation, the capacity of a 4x2 link with suppressed interference from one interfering BS is compared with the 4x2 MIMO capacity without interference. In this instance, significantly higher SNR, up to 20dB more, is required to achieve comparable capacity with the non interfered link as seen in Table 6 (a). Another way to carry out a valid comparison is in the cooperative case. The reference in this instance is a full 8x4 cooperative MIMO link (again with 10dB SNR) that would require higher complexity and communication between BS links. However, using the derived algorithm where weighting is controlled by the mobile, two 4x2 MIMO links it creates, which add up to 4 links with SINR_{pn} therefore have capacity as follows:

$$C = \sum_{n=1}^4 \log_2 (1 + \text{SINR}_{pn}) \quad (19)$$

As shown in Table 6 (b) a higher SNR of over 20dB more is needed to achieve comparable capacity but then this is a case of trade off between more required SNR and level of complexity to make cooperative use of the base stations. This therefore demonstrates how having two base station links is a question of either interference (to try and suppress the unwanted BS) or cooperation (to use links from both BSs to increase throughput). If there were 8 antenna branches at the mobile this could be expanded to create two 4x4 links at the mobile.

	Non Interfered 4x2 (SNR = 10dB)/ bits/s/Hz	Interference Suppressed 4x2 (SNR = 10dB)/ bits/s/Hz	Interference Suppressed 4x2 (SNR = 30dB)/ bits/s/Hz
Mean	11.23	5.53	15.36

(a)

Standard Cooperative 8x4 (SNR = 10dB)/ bits/s/Hz	Cooperative dual 4x2 (SNR = 10 dB)/ bits/s/Hz	Cooperative dual 4x2 (SNR = 30 dB)/ bits/s/Hz
32.61	10.95	30.83

(b)

Table 6 - Comparison of the resultant mean capacities with the appropriate reference case in the context of (a) 4x2 MIMO with suppressed interference and (b) dual 4x2 cooperative link for a single user

7. Conclusion

Simultaneous real time co-channel measurements of three 4x4 MIMO links to the same mobile on a cell boundary have been presented, providing evidence of non-orthogonality, which results in degraded capacity if seen as interference. Schemes have been presented through which the interference can be suppressed, though the cost results in increased SNR to gain comparable capacity potential. Strong SIR and good capacity in comparison with a non-interfered link have been seen to be possible with more than one base station present though there is a need for increased SNR, which is the main cost.

These results can also be seen another way around where there is an opportunity for increased capacity if new sub channels are created cooperatively. Schemes presented in this instance show a trade off between complexity and demand for increased SNR. Such co-operation would provide the benefit of 1:1 frequency reuse at cellular boundaries thus providing a soft handover possibility. This aspect of the results is open to further future analysis where schemes for MIMO or indeed combinations with CDMA can be investigated with a view of cooperation rather than interference.

8. References

1. J. Bach Andersen, "Array Gain and Capacity for Known Random Channels with Multiple Element Arrays at Both Ends", *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 11, November 2000, pp2172-2178.

2. F. Molisch, "A Generic Model for MIMO Wireless Propagation Channels in Macro- and Microcells", *IEEE Transactions on Signal Processing*, vol. 52, no. 1, January 2004, pp61-71.
3. D. Shiu, G. J. Foschini, M. J. Gans and J. M. Kahn, "Fading Correlation and Its Effect on the Capacity of Multielement Antenna Systems", *IEEE Transactions on Communications*, vol. 48, no. 3, March 2000, pp502-513.
4. K. Yu, B. Ottersten, "Models for MIMO Propagation Channels: A Review", *Wiley Wireless Communications and Mobile Computing Journal*, 2002, no. 2, pp653-666.
5. J-S Jiang, M. Faith Demirkol, M. A. Ingram, "Measured Capacities at 5.8GHz of Indoor MIMO Systems with MIMO Interference", *IEEE Vehicular Technology Conference*, vol. 1, 6-9th October 2003, pp388-393.
6. W. A. T. Kotterman, D. Prasad, K. Olesen, P. Eggers, I Z Kovacs, G. F. Pedersen, "Channel Measurement Set-up for Multi Antenna Handheld Terminal and Multiple (Interfering) Base Stations", *Wireless Personal Mobile Communications (WPMC)*, vol. 1, September 2001, pp153-157.
7. F. H. P. Fitzek, M. D. Katz, "Cooperation in Wireless Networks: Principles and Applications", 2006, *Springer*, The Netherlands.
8. R. G. Vaughan, J. Bach Andersen, "Channels, Propagation and Antennas for Mobile Communications", *IEE Press*, UK, 2003.
9. M. Schwartz, W. R. Bennet and S. Stein, "Communication Systems and Techniques", *McGraw Hill*, 1966.
10. W. A. Th. Kotterman, G. F. Pedersen, K. Olesen, P. Eggers, "Cable-less Measurement Setup for Wireless Handheld Terminals", *IEEE International Symposium on Personal Indoor Mobile Communications*, vol. 1, October 2001, pp. B112-116.
11. J. B. Andersen, J. Ø. Nielsen, G. F. Pedersen, K. Olesen, P. Eggers, E. H. Sørensen, S. Denno, "A 16 by 32 wideband multichannel sounder at 5 GHz for MIMO", *IEEE Antennas and Propagation Society Symposium*, Vol. 2, 20-25 June 2004, pp1263-1266.
12. J. Bach Andersen, "Propagation aspects of MIMO channel modelling" in "Space-Time Wireless Systems" (H. Bölcskei et al.), *Cambridge University Press*, 2006.
13. S. R. Saunders, "Antennas and Propagation for Wireless Communication Systems", 1999, *Wiley*, UK.
14. P. Kyritsi, G. Papanicolaou, P. Eggers, A. Oprea, "MISO time reversal and delay-spread compression for FWA channels at 5 GHz", *IEEE Antennas and Wireless Propagation Letters*, vol. 3, 2004, pp96-99.
15. H. Zhang, H. Dai, "Cochannel Interference Mitigation and Cooperative Processing in Downlink Multicell Multiuser MIMO Networks", *EURASIP Journal on Wireless Communications and Networking*, Issue 2, December 2004, pp222 - 235.