SPACE-TIME PROCESSING FOR 3RD GENERATION MOBILE WIRELESS SYSTEMS

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INTRODUCTION

With the substantial and continued growth in the use of mobile telephones many wireless operators are now looking for new technologies to allow their networks to achieve improved spectral efficiencies to support the demand for higher and higher traffic loading and the increasing demand for higher-rate wireless data services. Smart antennas are one such technology that can be exploited at the base station to improve carrier-to-interference ratio C/I and, in principle, are capable of impacting both the downlink and uplink performance.

The provision of downlink C/I enhancement through the use of smart antenna technology is a particularly significant challenge since, unlike the uplink beamforming problem, there is no way for FDD systems of directly measuring the instantaneous downlink propagation channel characteristics at the base station. Whilst feedback from the mobile terminal can be utilised to provide this measurement, this would involve additional messaging across the radio link and is really only suitable for lower mobility wireless applications. Hence, for an application involving significant dynamics, the downlink beamforming solution must generally be based around uplink channel measurements. Beam-steering solutions based on estimation of uplink angle of arrival can be usefully exploited on the downlink. However, the multipath angle spread influences how well the beam patterns are maintained, and hence ultimately dictates the achievable C/I performance gains.

The influence of the propagation channel on the directional characteristics of a narrow beam antenna is illustrated in Fig. 1. Here, we have conducted a field measurement at a dense urban central London location aimed at quantifying the effective beam coverage in a high multipath environment. In this example the directional antenna (30º beamwidth in azimuth) was mounted on top of a seven-storey building, just above the average surrounding rooftop height. A CW carrier (approx. 1900MHz) was then radiated and signal strength measurements recorded as a mobile transmitter was driven around the sector. A second carrier was simultaneously received by a reference ‘full sector’ antenna. The figure shows a contour map of the received signal strength indication (RSSI) of the carrier transmitted by the beam relative to the corresponding RSSI from the full sector carrier. This ratio compensates for LogNormal shadowing effects and the comparison more clearly illustrates the effective directionality of the beam pattern. An adequately long RSSI averaging period was used to reduce measurement errors on the RSSI values due to fast fading. Note that the black ‘outer’ markers indicate the effective edge of sector, whereas the brown ‘inner’ markers indicate the –4dB beamwidth of the antenna beam design.

The figure shows that there is some distortion of the beam coverage due to the multipath scattering. However, there is still good agreement between expected and actual mainlobe responses, and the sidelobe performance is shown to be maintained reasonably well. Overall, the result indicates that directional beamforming is still capable of supporting good C/I enhancement by simple spatial filtering even under harsh multipath conditions as experienced in a dense urban environment.

TDMA MULTIBEAM TRIAL

An extensive field trial has been conducted by Nortel Networks in collaboration with Cellcom, Israel of a MultiBeam antenna system with an IS-136 TDMA cellular network in the 850MHz band [1]. The objective of this trial was to confirm the viability of the MultiBeam product concept and to benchmark its performance in a typical high capacity RF deployment involving close-to-rooftop antenna installations and small cell sizes. The results obtained from this trial in terms of achieved C/I gain and other QoS metrics have been extremely promising.

The trial involved the deployment of MultiBeam antennas at three cell sites in the network at the city of Haifa. One of these represented the ‘target cell’ within which the major part of the performance characterisation was made. The other two cell sites represented the location of co-channel interferers on the downlink (i.e. co-channel frequency reuse cells). These were chosen such that the three cells together represented an N=4 frequency reuse cluster.

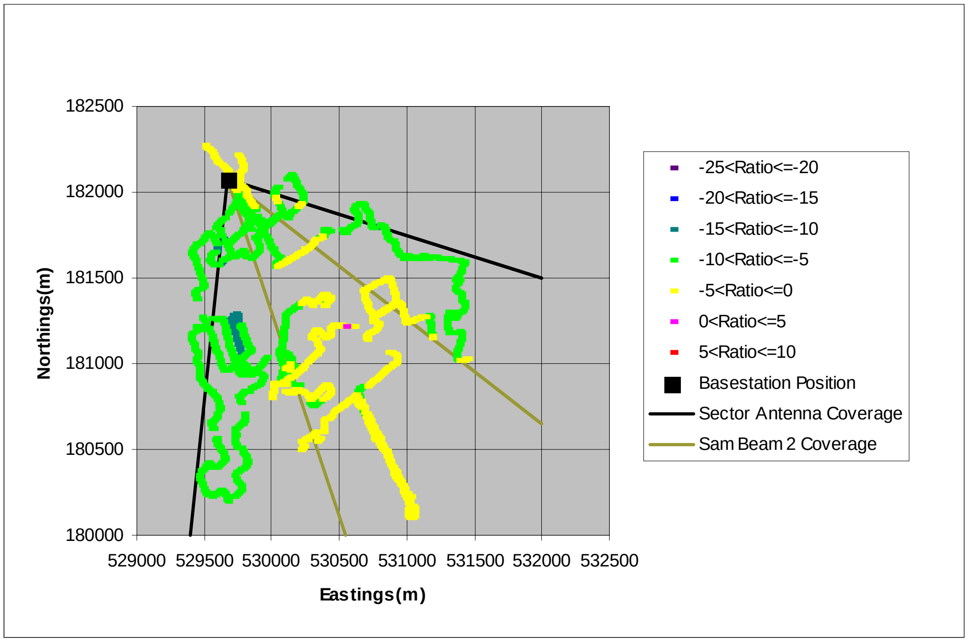

Fig.1: Beam coverage map measured in central London

A considerable amount of drive testing was conducted within the target cell to allow the C/I to be measured using both the existing full sector and MultiBeam antennas within the 'close to N=4' reuse cluster. The coverage of the drive route was sufficiently detailed to ensure good overall sampling of the LogNormal fade structure within the sector which was an important factor in being able to determine C/I gains with a good confidence level. The measurement results indicated a clear 3dB improvement in C/I using MultiBeam in direct comparison with the conventional 90° full sector system. This gain was realised on both up and down links. In both cases, the C/I gain resulted in a substantially improved BER performance, with a reduction in mobile transmit power possible on the uplink.

SMART ANTENNAS FOR 3^RD GENERATION SYSTEMS

Thus far in the discussion we have concentrated on the 'narrowband' smart antenna solution, i.e. where the instantaneous waveform bandwidth is somewhat less than the reciprocal of the maximum delay spread in the channel. The design and analysis of smart antennas for 3rd Generation applications (e.g. wideband CDMA systems such as cdma2000 or UTRA) becomes more complicated. Now, the system must also take into account the spatial and temporal aspects of the channel in order to optimise the air interface capacity gain. A thorough understanding of the likely angle scatter and delay spread within the channel is necessary to tackle such a design.

Extensive measurements have been conducted by the Radio Technology group at Nortel Networks' Harlow Labs in order to characterise the radio channel for 3rd generation mobile systems. This work has utilised a special measurement facility, the Aperture Analyser, which is capable of determining the joint angle/delay spread phenomena. Fig. 2 shows a scatter map measured in central London in the 1.8GHz to 1.9GHz band. This example contour map presents received signal strength as a function of relative delay (horizontal axis) and relative angle (vertical axis), and indicates a number of dominant scattering centres over a 55° angle spread and a 1μs time interval. This particular measurement corresponds to the base station receiver being located on top of the Engineering faculty building at University College, London and the mobile transmitter located in Great Marlborough St. at a range of about 1km.

Many such measurements have been conducted in central London, and these results have been analysed to determine the distribution function of angle scatter and delay spread for the typical dense urban environment. These measurements have then been used to compare a range of candidate smart antenna algorithms, in particular assessing comparative performance gains when taking into account the spatial/temporal processing constraints.

The use of smart antennas to achieve increased air interface capacity of the forward link in a CDMA system calls for two key requirements to be met:

(i) Forward link transmissions should ideally be focussed directly towards mobiles within the wanted sector in order to reduce the level of interference across the rest of the network.

(ii) The mobile must not be denied available path diversity, since this can be exploited to optimise the reception of signals and so mitigate the effects of fading. With the wideband CDMA application it may be undesirable to allow the smart antenna to provide directional transmission at the base station if this unduly compromises the effective link diversity to the mobiles. An exception to this is if the directional transmission helps preserve code orthogonality on the forward link thereby reducing self-interference effects. Diversity gain could alternatively be provided in a CDMA system by soft handoff.

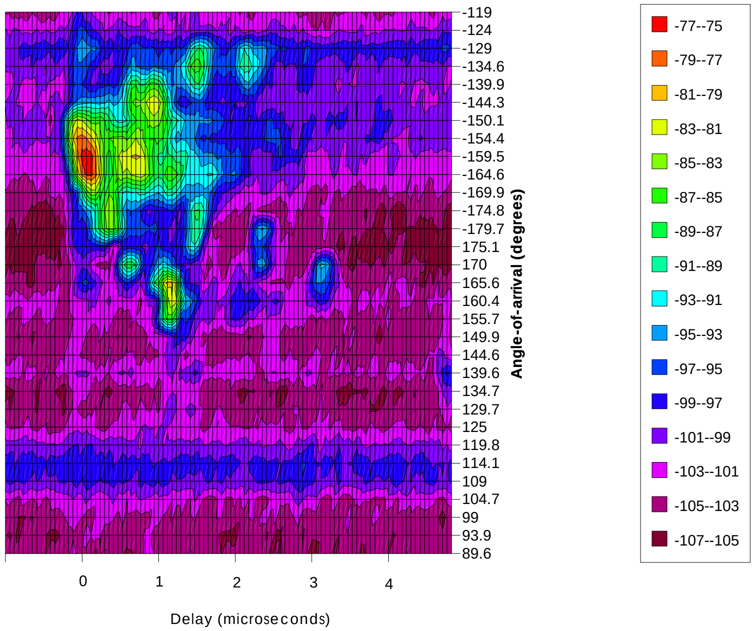

Fig.2: Example Scatter Map measured in central London

For the purpose of this analysis we introduce a quantity which we term the ‘forward link capacity gain’ FLCG defined as the combination (in dB) of the azimuthal illumination gain (AIG) and the diversity gain (DG). Hence we have:

$$\mathrm{FLCG}_{\mathrm{dB}} = \mathrm{DG}_{\mathrm{dB}} + \mathrm{AIG}_{\mathrm{dB}} \tag{1}$$

Here, $\mathrm{AIG}_{\mathrm{dB}}$ describes the interference reduction capability of the antenna system and is essentially the usual directivity measure of the antenna but with the integral of gain taken only over the azimuthal plane. $\mathrm{DG}_{\mathrm{dB}}$ describes the relative diversity gain of the antenna system compared with that achieved by a single antenna. This diversity gain measure must take account of time diversity due to the multiple delay paths in the channel, spatial diversity effects due to deploying an antenna array, and other similar factors.

In a CDMA system FLCG reflects the average capacity gain provided by the smart antenna solution in the limiting case of there being a large number of narrowband voice users per cell. Both of these parameters, $\mathrm{DG}_{\mathrm{dB}}$ and $\mathrm{AIG}_{\mathrm{dB}}$, can be readily estimated for candidate smart antenna configurations if the angle scatter/time delay features of the channel are known.

Fig. 3 plots the variation of FLCG for the case of a 4-element, ½ wavelength spaced, linear antenna array. The graph shows the variation of FLCG for a number of the real channel scenarios measured by our propagation trial programme. Various beamforming algorithms have been considered as described in [2]:

(i) Bearing Estimation Beamforming - the basic principle is to estimate the mobile bearing based on the reverse link covariance matrix (i.e. an aggregate of all time taps), and to use this bearing to point a plane-wave beam on the forward link.

(ii) Max-SNR Beamforming – an eigenvector decomposition of the reverse link covariance matrix (over all time taps) is calculated and the eigenvector corresponding to the largest eigenvalue is used as the beamformer weighting to achieve maximum power transfer on the forward link. No correction is made to try to account for any frequency spacing between reverse and forward links.

(iii) Constrained Downlink Beamforming – this tries to improve performance in certain cases (where available time diversity may be degraded by either of the two techniques above) by the spatial beamforming process. It finds the eigenvector (corresponding to the largest eigenvalue) for each channel tap covariance matrix on the reverse link. The constrained beamformer is then calculated to apply 'equal gain' in directions of all eigenvectors.

The above techniques are more appropriate to an application involving a compact antenna array rather than a wide-spaced diversity antenna. Also, beam adaptation is assumed to be a moderately slow process, i.e. slower than the maximum Doppler in the channel, but at a sufficiently fast rate to track mobile dynamics and shadowing effects.

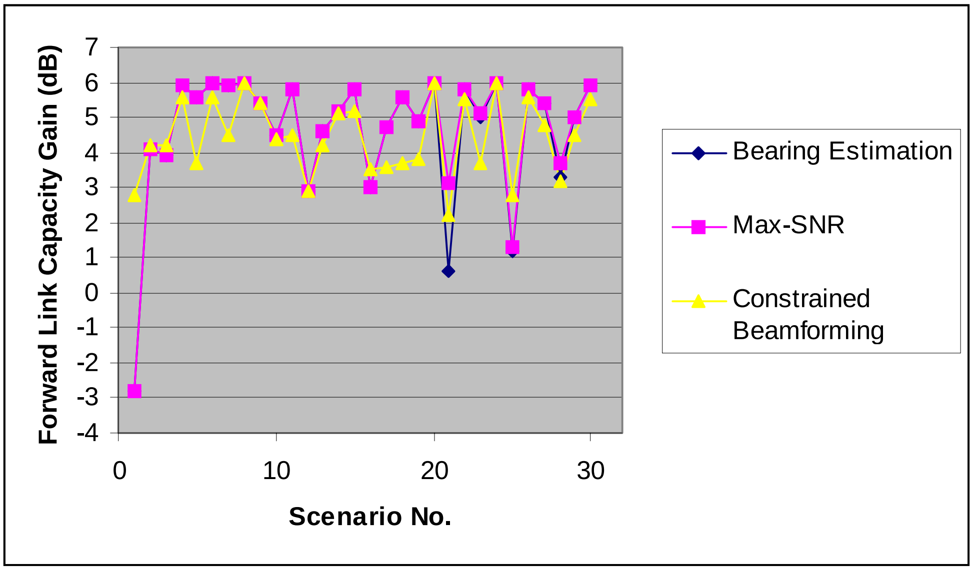

Fig.3: Comparison of Forward Link Capacity Gain (FLCG) using candidate smart antenna algorithms

Note from Fig.3 that there is an upper bound on the FLCG of 6dB due to only 4 elements being used by the smart antenna array. All three algorithms achieve better than 3dB gain for 27 out of the 30 propagation scenarios (and better than 4dB gain for approx. 2/3 of the scenarios). The Bearing Estimation and the Max-SNR techniques provide very similar performance for most of the scenarios. Poor performance is observed for the case of scenario #1 using these methods and this is due to the fact that the downlink beamforming has prevented the illumination of multiple time-delayed scatterers which, in turn, has denied the mobile from obtaining a considerable amount of inherent diversity advantage. The Constrained Beamforming approach helps recover this performance loss.

CONCLUSIONS

This paper has shown that significant C/I gain is feasible using smart antenna solutions. These gains are achievable even in highly complex multipath scattering environments.

Nortel Networks has successfully carried out the world's first live-air demonstration of a MultiBeam smart antenna solution on Cellcom's TDMA network in Israel. This achieved a 3dB improvement in C/I performance on both uplink and downlink. The trial was undertaken in an extremely demanding RF propagation environment with small cell sizes and the base station antennas mounted close to average rooftop heights. The trial confirmed that directional beamforming still represents an effective technique for reducing interference under such conditions

A propagation trial campaign has also been conducted in the 1800-1900MHz band to establish viable smart antenna approaches for 3G. The detailed characterisation of the angle and delay spread scattering phenomena obtained from these trials has enabled the comparison of the relative performance gains of several smart antenna schemes under realistic channel conditions. The conclusion reached from this analysis is that smart antenna solutions using compact antenna arrays at the base station should be capable of providing worthwhile capacity gains in typical dense urban deployments.

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