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# European Technological Advances in Smart Antennas

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***Abstract:*** *The European Commission, through RACE, ACTS and now the IST programmes, has funded numerous consortium based research projects addressing capacity enhancement by means of Smart or Adaptive Antenna Technology. In addition to capacity enhancement, these projects have also considered additional operational benefits, such as multipath mitigation and range extension, that this technology can offer wireless network deployments. This paper[1] provides an overview of the key results obtained from the test beds and field trials conducted under the RACE and ACTS TSUNAMI projects as well as ACTS AWACS project. Further, new research activities, which embody Smart Antenna Technology, now supported under IST funding are also introduced.*

## 1. Introduction

In order to realise the full potential of, ‘Any Where, Any Time Personal Communications’, which will include high bit-rate real-time multimedia applications, time-space adaptive signal processing is now regarded as a core element within future system deployments. It is envisaged by those engaged in wireless system design that time-space processing in the form of adaptive or Smart antennas[1], as well as adaptive interference cancellation methods[2], will provide the long-term means to offer sufficient user capacity within the confines of the limited radio spectrum allocated to these systems. Conventional ‘Smart’ antenna systems yield a capacity enhancement or range extension over conventional fixed beam antenna installations by focussing their beam patterns towards an addressed volume associated with the signalling space of the desired traffic channel. This both reduces the interference[3] caused by, and also seen by this channel, hence providing a capacity enhancement through Spatial Filtering Interference Reduction (SFIR), or Space Division Multiple Access (SDMA).

Numerous test-beds or validators have also been constructed in order to provide further ‘proof-of-concept’ as well as inform the industry and network operators about this new technology. This has been conducted both privately within numerous organisations, as well as publicly under initiatives such as the European RACE[2] and ACTS[3] programmes. Under these frameworks, field trial demonstrations of the operational benefits obtainable via range extension, delay spread or multipath reduction and capacity enhancement by means of both SFIR and SDMA have been shown. In particular, both RACE and ACTS TSUNAMI (Technology in Smart antennas for the UNiversal Advanced Mobile Infrastructure) have demonstrated range extension and SFIR, RACE TSUNAMI and ACTS AWACS (ATM Wireless Access Communication System) delay spread reduction, and SDMA operation through RACE TSUNAMI. These projects are now presented in a chronological order, with key aspects highlighted in order to reinforce the benefits of smart antenna technology by means of practical illustration drawn from the field trial results.

## 2. RACE TSUNAMI [4]

This project (January 1994 to December 1995) provided the first field trial evaluation of adaptive antenna technology under European funding. The consortium conducted systems analysis by means of computer simulations, multi-sensor propagation measurements and a field trial validation of range extension, delay spread reduction, SFIR and SDMA. Given that ACTS AWACS and ACTS TSUNAMI (see sections 3 and 4 respectively) have now provided further results with regard to the former operational benefits, only the SDMA trials obtained will be described here.

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[2] Research into Advanced Communications for Europe
[3] Advanced Communications Technologies Societies

Under the RACE TSUNAMI project an 8 element transmit and receive adaptive antenna test bed was constructed, operating in conjunction with the European DECT radio standard. Beamforming was by means of IQ base-band digital weighting and control via a pair of TMS320C40 digital signal processors. The embedded DECT radios were modified such that they only operated on a single fixed frequency and single timeslot, thus supporting the SDMA concept. These radios were also capable of supporting speech, data and channel quality assessment measurements (received signal strength and bit error rates) made during the trials.

Figure 1a shows one of the test environments used for the SDMA trials[5] as well as the 'user' starting positions. This operational area is a typical outdoor urban environment and was sited adjacent to the Engineering Buildings at the University of Bristol. The smart base station antenna was configured as a $\lambda/2$ linear array installed at a height of approximately 30m above the ground on a window ledge over looking the test sites. Initially, two users moved towards each other at walking pace (see points 1 and 2) to a position where their angular separation was just less than 15°, when viewed the base station. At this point the users stopped and returned to their original positions, thus ensuring that their angular tracks did not cross and the angular separation was always greater then the 3dB beamwidth of the antenna array. The direction of arrival information (DoA) obtained from the array via the MUSIC algorithm as given in Figure1b was used to control a pair of digital beamformers.

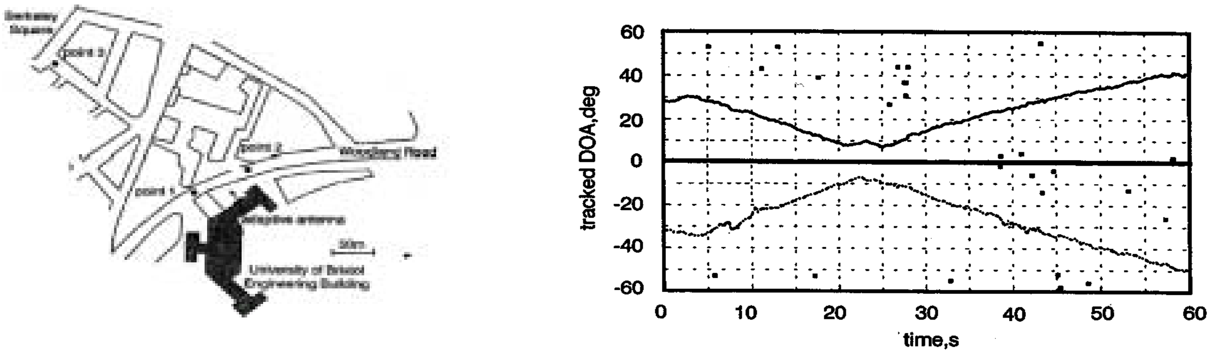


Figure 1: (a): Map of SDMA Trials (Left), (b): DoA tracking of SDMA users [5] (Right)

By examining Bit Error Rate (BER) of the up and downlinks for both users (Figure 2), it can be seen that wireless communications via SDMA is possible for this scenario, given that the instantaneous BER is less than $10^{-3}$ for most of this experiment. If the user tracks were allowed 'to cross' during 'SDMA', then both DoA tracking and communications was lost. Hand-over out of 'SDMA mode' is thus required in order to support full mobility.

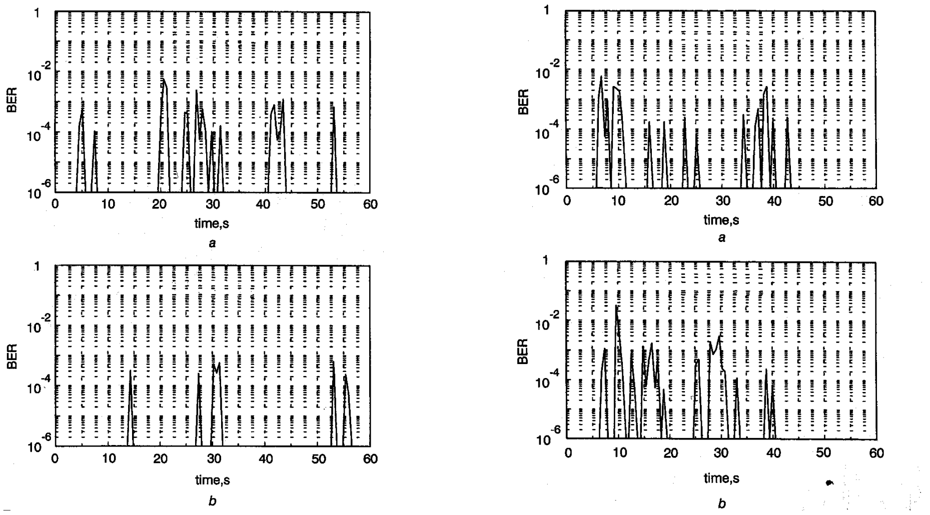


Figure 2 Instantaneous BER for user A (left) and user B (right) for SDMA mode.
Upper plots for Uplink, Lower Plot for Downlink[5].

# 3. ACTS AWACS[6]

The ACTS AWACS project addressed the feasibility of directional antenna technology as a viable alternative to equalisation and multi-carrier techniques for the provision of ATM compatible bit rates over a wireless bearer. In addition to the wideband propagation analysis and transceiver trials, the project also addressed alternative modulation and coding schemes, Medium Access Control (MAC) protocols, and potential use of 40 GHz carrier frequencies, as well as mobility aspects of wireless ATM service provision. The main goal of AWACS was to support and influence emerging ATM wireless standards, in particular the new HIPERLAN type 4 or HIPERLINK specification.

Of particular interest here is propagation measurement and analysis activities as well as the wireless modem performance evaluation. Using a wideband channel sounder operating at a carrier frequency of 19.34GHz and a chipping rate of 100Mchip/s, the rms delay spread distribution of various indoor operation scenarios was obtained [7] for numerous antenna beamwidths. For each set of measurements, the antennas were manually aligned to face each other, even if objects blocked the line of sight path.

In figure 3 it can be seen that the performance of the 60°-60° arrangement is better than the omni-15° approach in terms of rms delay spread, although both configurations have a similar combined gain. Further, the results clearly indicate that low rms delay spreads can be achieved with correctly orientated narrow beamwidth antennas. If an rms delay spread window of 20ns is assumed, then for this operational area the 15°-15° configuration achieves 100% coverage, whereas the 60°-60° can provide up to 90% coverage. Further, with an omni-antenna at the mobile station (MS), a 15° antenna was necessary at the central station (CS) in order to achieve 75% coverage. For 30°and 60°antennas at the CS, coverage drops to around 40% of locations. It should be noted that all these measurements were taken within 25m of the CS.

The relationship between rms delay spread and Rician K-factor was evaluated as shown in figure 4. The graph shows that the K-factor remains high (>7 dB) for values of rms delay spread less than 20ns. As the rms delay spread increases, there is a greater possibility of encountering low K-factors, and hence severe fading. For example, with 15° beamwidth antennas, the lowest measured K-factor was 12 dB and the highest rms delay spread was 10ns. However, for an omni-omni configuration, the K-factor can be as low as -6 dB (Rayleigh-like) and the rms delay spread as high as 150ns. The Table within the figure shows the extreme K-factors and rms delay spreads for mixed antenna solutions.

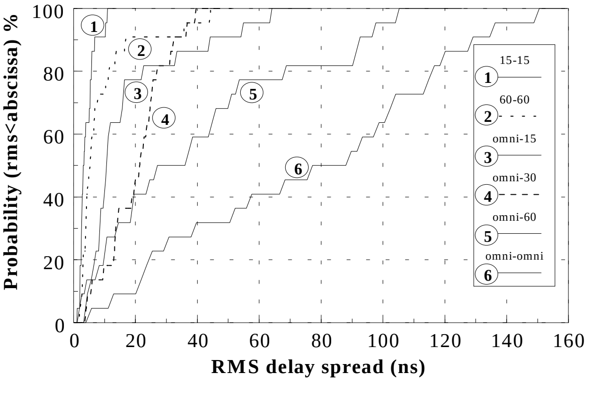
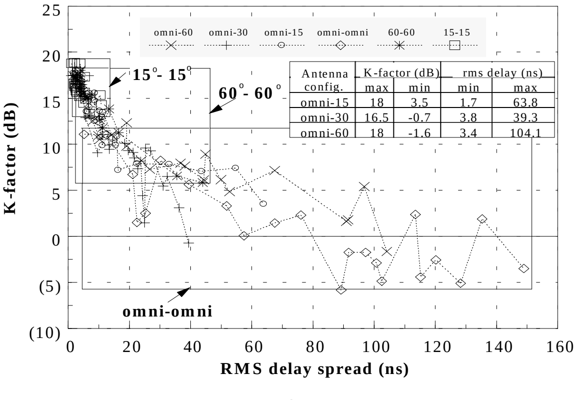


Figure 3: RMS delay spread reduction with directive antennas (Antenna Beamwidth quoted in box)



| Antenna config. | K-factor (dB) |  | rms delay (ns) |  |
|---|---|---|---|---|
|  | max | min | min | max |
| omni-15 | 18 | 3.5 | 1.7 | 63.8 |
| omni-30 | 16.5 | -0.7 | 3.8 | 39.3 |
| omni-60 | 18 | -1.6 | 3.4 | 104.1 |

Figure 4: Rician K-factor against rms delay

In order to investigate the relationship between the channel parameters and the corresponding Bit Error Rate (BER) performance of the 'AWACS transceiver', an HP ATM test-set was used in-conjunction with the hardware platform. The hardware [8] employed a QPSK modem operating at a maximum data rate of 34Mbit/s, with out any form of equalisation, although Forward Error Correction (FEC) was used on both the ATM header and payload. Transceiver performance trials were carried out for both macro and microscopic motion within the service area, as well as the impact of the distribution antenna directivity was considered in detail. Figure 5 now shows the comparison between the performance of different antenna combinations.

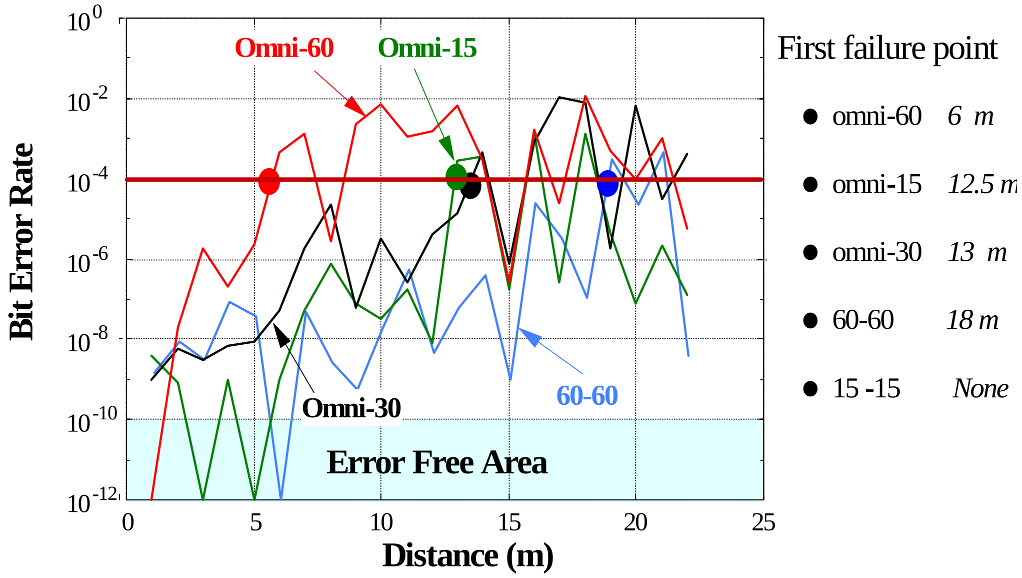


Figure 5: BER performance comparisons for different antenna configurations.

It can be clearly seen (figure 5) that as directivity of the antenna is enhanced, the BER of the system improves considerably. For example, if a threshold of $10^{-4}$ is assumed for BER performance, then the 15°- 15° antenna configuration will always be below this value for the route or service area under consideration (Note these results do not include ARQ). For 60°-60° combination the error threshold was exceeded when the receiver was >18m away from the Base station. For Omni- 60° combination, only a 6m path could be supported. Furthermore, considering the combined antenna gains of the Omni-15° and 60°- 60° configurations (both have a combined gain of about 20 dBi), it can be seen that the deployment with twin directional units has a better performance than that with the same combined gain.

## 4. ACTS TSUNAMI[9]

The main objective of the ACTS TSUNAMI II project was to demonstrate that it is feasible and cost effective to deploy adaptive antennas within the infrastructure of third generation mobile systems such as UMTS. Justification for the former has been given through the field trials outlined below using DCS1800 as the donor air interface and here issues such as environment perturbation to the antenna performance, array calibration, mobile tracking performance and range extension are discussed. The specific issues related to UMTS operation (wideband spatial and temporal array processing methods) were also considered under both TSUNAMI and a follow-on project known as ACTS project SUNBEAM[10].

The development, integration and field trial evaluation of a basestation with an adaptive antenna facet operating over a mobile radio air interface was a major aspect of the work conducted under the CEC ACTS TSUNAMI (II) project[11]. Here the consortium designed and constructed an 8 element transmit and receiving adaptive antenna system, employing digital beamforming techniques operating over a DCS1800 air interface. A suite of antenna array control algorithms were ported on to this platform, and the performance assessed for a variety of different operational scenarios using the Orange Test-bed facility in Bristol (UK).

The software based antenna array control system supported multi-element diversity combining, in the form of: Maximal Ratio Combining (MRC), spatial control methods such as MUSIC (with spatial smoothing) and Grid of Beams (GoB). Also supported were the temporal methods of: Optimal Combining (OPT) and a grid of beams method using beam selection based on wanted user training sequence correlation (known as the AUC algorithm). In order to ascertain the relative performance of these algorithms, the following information was logged during the field trials:

- The signal strength, quality metrics (RxQual) and timing advance.
- The GPS location of the wanted mobile.
- The estimated uplink signal strength received at each element of the array, and the beamformer output.
- The call quality metrics (RxQual) for the uplink (wanted mobile to basestation).
- The direction of arrival (DoA) information produced by the adaptive beamforming algorithm, and the Tx and Rx weight vectors synthesised by the adaptive processing.

The TSUNAMI field trial system included transmit and receive calibration in order to support the use of digital beamforming techniques[12]. The drift in the multiple analogue upconversion and downconversion chains was monitored over time in conjunction with the indoor and outdoor ambient temperature. This was used to investigate the requirements for an adaptive antenna calibration scheme, which would be applicable to potential commercial systems of the future. It was found that variations in the individual amplitude and phase transfer functions of each element, over a continuous 96 hour operational period, could exceed 1dB and 6° respectively. This would require an estimated minimum of 55 re-calibrations over the period, in order to meet the target specifications. It was also noted that the period between these calibration points varied between 1 minute to 18 hour intervals, thus suggesting an update rate of less than 1 minute intervals for the hardware developed here.

For macrocellular deployment, it was found that the beamwidth of the antenna was approximately 12°, with a typical first sidelobe level of 10dB and a typical null depth of between 13 to 20dB (figure 6). It was also noted that the beam pattern was greatly impaired by scattering in non line-of-sight regions with the antenna (increasing the sidelobe level and decreasing the null-depth). This was found to be very acute in the microcellular trials[11].

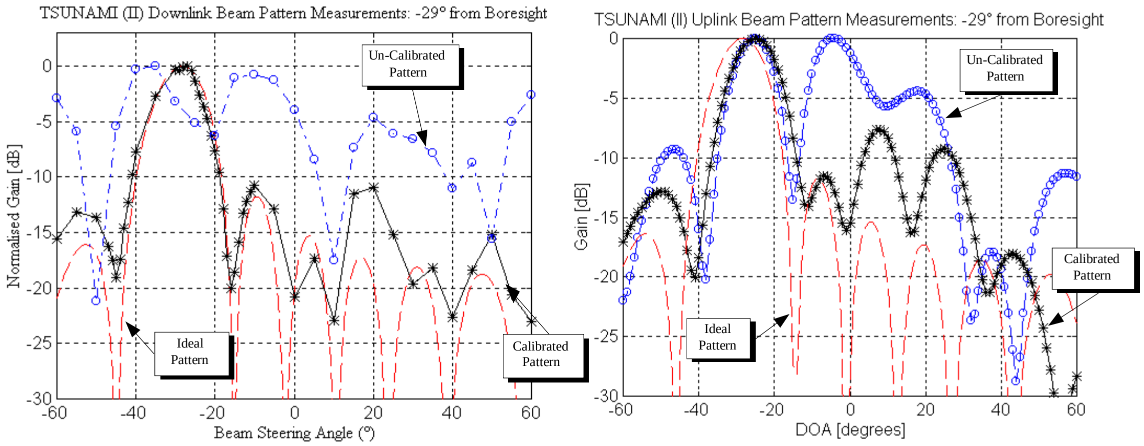


Figure 6: An Example of the Measured Antenna Response (Macrocellular).

The ability to track users is a fundamental aspect of this technology. Here, the ability of each candidate control algorithm to track a user was appraised and compared with position location, obtained via a commercially available GPS receiver. In the course of the macrocellular trials it was found that the tracking accuracy was affected by the infrequency of the uplink calibrations which resulted in offsets of upto 6°. A summary of the results obtained is given below in Table 1.

| | **MRC** | **GoB** | **OPT** | **MUSIC** | **AUC** |
|---|---|---|---|---|---|
| **Mean** | +6.1 | +5.7 | +6.1 | +6.0 | +1.2 |
| **RMS** | 6.4 | 6.7 | 7.4 | 6.1 | 2.2 |
| **STD** | 1.9 | 3.5 | 4.3 | 1.1 | 1.9 |

Table 1: Direction of Arrival Error Statistics (Degrees)

One of the key operational benefits of adaptive antenna technology is the ability to reduce the degradation in system performance due to interference. As part of the TSUNAMI field trials the interference rejection capability of the candidate control algorithms was appraised for both stationary and dynamic scenarios. Some of the algorithms exploit the cross-correlation properties of the DCS1800 training sequence. The ability of these algorithms to reject interference, was found to be dependent on the nature of the interfering signal (continuous wave or GMSK). In most cases, the results indicate that a beamformer gain can be obtained for signal separations (wanted to interferer) for as low as 10°.

Array signal processing offers increased directivity over a single element or non-adaptive case as illustrated in figure 7. It can be seen that algorithms that rely on beam steering, fall short of achieving the theoretical available gain (9dB) by at least 1dB. This suggests that the uplink calibration of the system is not ideal. Optimal Combining comes very close to achieving the 9dB maximum gain for the majority of the experiment. However, this algorithm is less stable than MUSIC or Grid-of-Beams and exhibits regions of very low gain. The dynamic directivity illustrated here can be exploited in terms of range extension of a given cell site. This aspect was considered during the TSUNAMI (II) trials, with both the MUSIC and AUC algorithms providing significant enhancements to the coverage of the test cell. Direct measurement of the link quality obtained during the trials indicates a 54% range enhancement in terms of increased cell radius, whereas using the measured gain of the antenna yields a predicted increase of 62% (assuming a path loss exponent of 3.5 and a frame error rate of 1%).

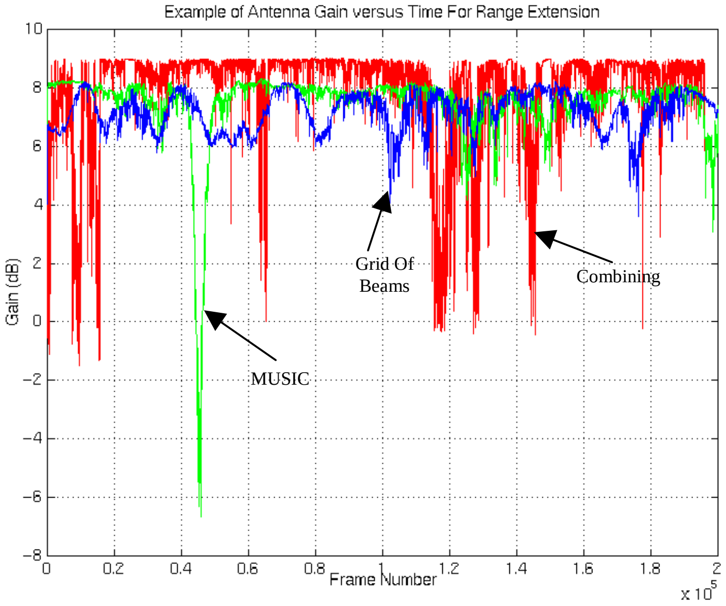


Figure 7: Measured Uplink Beamformer gain.

## 5. IST Programme[13]

Despite the success of the TSUNAMI field trials as reported above, 3rd Generation Wireless networks (e.g. UMTS) could still fall short of market expectations in terms of available capacity for 'e-commerce' and 'multi-media' based services. The Smart antenna technology considered here and elsewhere has been largely based on a single array operating in conjunction with a fixed radiating element in order to obtain the spatial signature of the environment. It is well understood that this architecture can be employed to obtain multiple fading signals from a multipath rich environment and a processing gain realised through the application of optimum combining. In essence this technique exploits the fact that the spatial samples obtained from the array have undergone independent fading. As recently reported in the literature[14], this concept can be extended by employing spatial arrays at both ends of the communication link, thereby exciting multiple independent paths or spatial channels from each of the transmitting elements to each element within the receiving array. Given that these multiple channels can be processed in such a way that they appear orthogonal, this novel application of spatial signal processing offers a significant capacity enhancement (higher bit rate using the same bandwidth) over the single array topology. This technique, if practically viable, will offer a unique solution for bandwidth hungry wireless applications.

The European Commission through the Information Societies Technologies (IST) programme are currently supporting two new projects addressing Multiple-Input Multiple-Output (MIMO) technology. The METRA[15] project is addressing transmit diversity in the context of W-CDMA within UMTS, whereas SATURN[16] is looking at the application of MIMO signal processing for wireless LAN based applications.

## 6. Conclusions

An experimental validation of smart antennas within the context of future generation wireless networks as funded by the European Commission has been presented here. It has been clearly shown that spatial filtering can yield a significant reduction of interference both ‘seen-by’ and ‘caused-by’ a wireless network. Radio planners can exploit this reduction in interference levels in order to obtain a capacity increase for cellular-like deployments. Further, the benefits of ‘dynamic’ directivity have been shown in terms of cell site range extension of a 54% increase in cell radius for an 8-element facet. In addition, directivity was also shown to significantly reduce multipath activity for indoor high bit rate systems extending the operation range for a non-equalised system by a factor of 3 or more. New research is now underway in Europe addressing advanced smart antenna technologies, MIMO signal processing, with this approach potentially holding the ‘key’ to the capacity dilemma within wireless networks.

## Acknowledgements

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