Tsoulos, G. V., Beach, M. A., & McGeehan, J. P. (1997). Wireless personal communications for the 21st century : European technological advances in adaptive antennas. IEEE Communications Magazine, 35(9), 102 - 109. 10.1109/35.620531

ABSTRACT

Adaptive antennas are now regarded by many within the wireless communications industry as a core system component in future-generation mobile networks. In order to promote European research and development in this strategic area, the Commission of the European Community has funded, through the Research into Advanced Communications in Europe, RACE, and now the Advanced Communications Technologies and Services, ACTS, programs, the Technology in Smart Antennas for Universal Advanced Mobile Infrastructure, TSUNAMI, consortium in order to further technological advances for the next millennium, as reported here.

Wireless Personal Communications for the 21st Century: European Technological Advances in Adaptive Antennas

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Over the last few years the demand for service provision via the wireless communication bearer has risen beyond all expectations. At the beginning of the last decade some analysts predicted that fewer than 1 million Americans would use cellular radio services by the year 2000 [1]; however, today in excess of 20 million utilize this technology. At present the number of cellular users is growing annually by approximately 50 percent in North America, 60 percent in western Europe, 70 percent in Australia and Asia, and more than 200 percent in South America's largest markets. The extraordinary fact that some half a billion subscribers to mobile networks are predicted by the year 2000 worldwide introduces the most demanding technological challenge: the need to increase the spectrum efficiency of wireless networks.

The two systems that have been proposed to take wireless communications into the next century are the International Mobile Telecommunications-2000 (IMT2000) and the European Universal Mobile Telecommunications System (UMTS) [2]. The core objective of both systems is to take the "personal communications user" into a new information society where mass market low-cost telecommunications services will be provided. In order to be universally accepted, these new networks will have to offer mobile access to voice, data, and multimedia facilities in an extensive range of operational environments, as well as economically supporting service provision in environments conventionally served by other wired systems. It is against these forecasts that existing mobile communication systems will require radical reformation in order to meet the UMTS/IMT-2000 goals. Currently favored proposals include improved air interface and modulation schemes, deployment of smaller radio cells with combinations of different cell types in hierarchical architectures, and advanced signal processing. However, none of these schemes fully exploits the multiplicity of spatial channels that arises because each mobile user occupies a unique spatial location.

Filtering in the space domain can separate spectrally and temporally overlapping signals from multiple mobile units. Thus, the spatial dimension can be exploited as a hybrid multiple access technique complementing frequency-division multiple access (FDMA), time-division MA (TDMA), and code-division MA (CDMA). This approach is usually referred to as SDMA (space-division multiple access) [3], and enables multiple users within the same radio cell to be accommodated on the same frequency and time slot, as illustrated in Fig. 1. Realization of this filtering technique is accomplished using an adaptive antenna array, which is effectively an antenna system capable of modifying its time, frequency, and spatial response by means of amplitude and phase weighting and internal feedback control, as shown in Fig. 2. Numerous approaches using adaptive antennas have been considered in order to exploit the spatial domain; for example, null steering to isolate co-channel users [4], optimum combining to reduce multipath fading and suppress interference [5–10], and beam steering to focus energy toward desired users [11–13]. By exploiting the spatial domain via an adaptive antenna, the operational benefits to the network operator can be summarized as follows [14]:

- Capacity enhancement
- Coverage extension
- Ability to support high data rates
- Increased immunity to "near–far" problems
- Ability to support hierarchical cell structures

Adaptive antennas are now regarded by many within the wireless communications industry as a core system component in future-generation mobile networks. In order to promote European research and development in this strategic area, the Commission of the European Community has funded, through the RACE and now the ACTS programs, the TSUNAMI consortium in order to further research technological advances for the next millennium, as reported here.

Initially, a two-year (1994–1995) project with the acronym TSUNAMI was funded under the RACE funding initiative.

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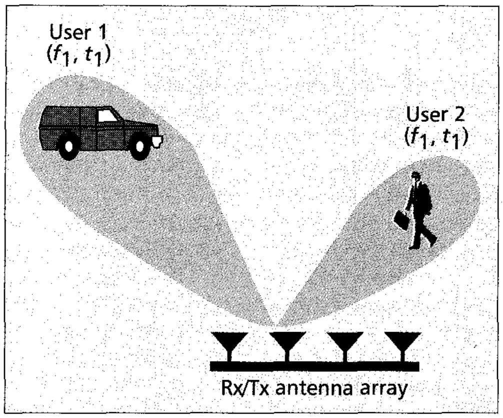
The focus of this project was the demonstration of the SDMA technique embedded within a wireless communications system [3]. In order to achieve this goal, the consortium developed state-of-the-art component technologies, conducted numerous spatial propagation trials, and performed extensive system simulations. It is against this background that the highlights of the RACE TSUNAMI project are now discussed. In addition, a new follow-up activity funded under the ACTS program is currently underway and is also briefly introduced.



■ **Figure 1.** *SDMA concept.*

Enabling Technologies: State of the Art

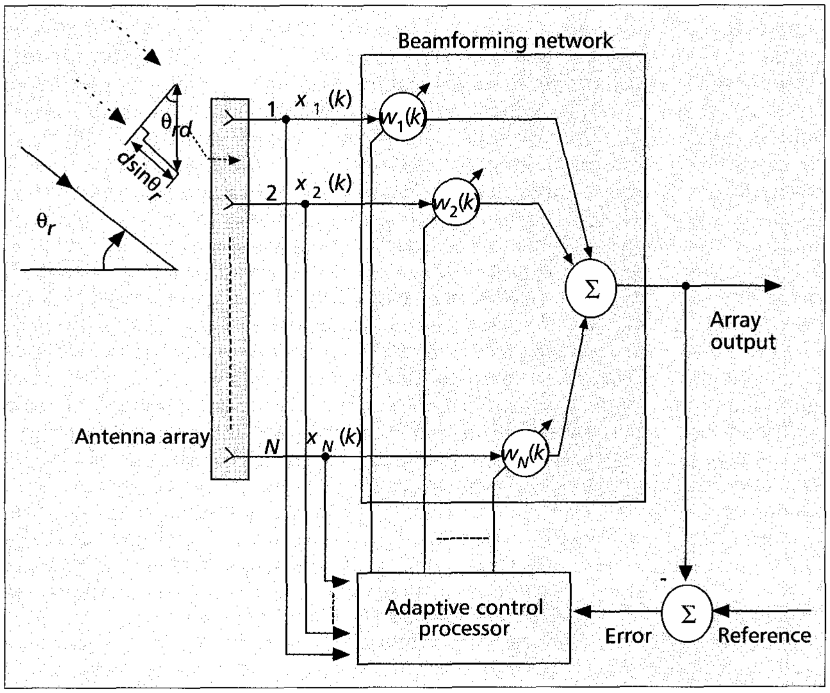
Beamforming Architectures to Support SDMA

The term *digital beamformer* (DBF) refers to a processing structure that accepts digital signals from the multiple sensors in an antenna array and then performs spatial processing on them. More precisely, the array antenna samples the electromagnetic waves at different locations in the antenna's aperture; the signals from each receiving element are converted to complex digital numbers at high sampling rates and transferred to the DBF. The origins of the DBF processing scheme date back to the traditional phased array approach, or radio frequency (RF) or intermediate frequency (IF) beamforming [15–16], where the signals collected from the antenna array are shifted in phase, summed in an analog device, and subsequently downconverted to baseband. The principal disadvantage of performing the weighting process in the RF or IF analog domain is that it is relatively inflexible, and can become extremely complex as the number of SDMA channels to be generated increases. Beamforming at IF, compared to RF beamformers, offers the potential for lossless beamforming on receive; hence there is potential for greater precision in phase shifter and attenuator control. The advantages of performing the beamforming process in the digital domain at baseband, rather than at RF or IF, may be summarized as follows [17]:

- A high degree of accuracy and control of the antenna pattern. 16-bit precision is readily available for the complex multiplier used to apply the element-level phase and amplitude coefficients, as compared to a technological limit of 5 to 6 bits for the equivalent analog phase shifter and attenuators required for RF or IF beamforming.
- The complete complex array of signals from the antenna aperture is available for calibration and spatial processing. This enables sophisticated array calibration techniques to be implemented with a minimum of additional hardware, and also high-precision user location or acquisition algorithms to be employed with DBF.
- A large number of overlapping beams can be generated by multiplexing the same DBF hardware between the weight vectors defining the look direction of each user.
- Digital beamforming can be combined with channel-level FDMA multiplexing and demultiplexing, using efficient DSP filtering techniques, in order to implement highly flexible multiple-channel/multiple-beam systems with overlapping beams and frequency reuse between adjacent beams [17, 18].

The main disadvantage of a DBF technique relates to the system complexity, which increases with the signal bandwidth, number of array elements and number of simultaneous beams. Other limitations include availability, cost, frequency, and dynamic range characteristics of analog-to-digital and digital-to-analog converters, and the data rate required for the digital beamformer. However, efficient implementations are possible (e.g., in the form of a triangular systolic processor [19]), resulting in highly modular, low-complexity, low-cost systems. Furthermore, despite the limitations mentioned above, adaptive antenna technology can still offer a cost-effective method of improving the performance of wireless networks.

The logical extension of the conventional receive-only adaptive antenna system is the receive and transmit beamforming architecture employed in the TSUNAMI testbed. However, this method requires state of the art RF subsystem components.



■ **Figure 2.** *The adaptive antenna concept employing a temporal reference beamforming technique.*

Linearized Feedforward RF Power Amplifiers

The use of DBF techniques poses high linearity demands on both the RF/IF up- and downconversion chains [20]. This is because the weights of the beamformer are carefully calculated and constructed at the digital baseband; thus, any distortion in the up- or downconversion chains will alter the produced antenna beam pattern and the ultimate performance of the adaptive antenna. This effect is most noticeable in the transmit chain; however, high-dynamic-range receiver aspects were also addressed by the TSUNAMI consortium in order to fully address third-generation hardware implementations. Some of the fixed mismatches between channels can be corrected using online calibration techniques, but nonlinearity effects in the transceiver chain cause both intermodulation distortion and gain-phase variations with different "drive" levels which cannot be calibrated out in any practical way. These intermodulation products (IMPs) and power-dependent offsets will ultimately render the adaptive antenna useless in terms of spurious radiation, spatial domain channel blocking, and wanted beam pattern misalignment. In [21] it was shown that as the level of nonlinearities increases, the sidelobe level increases and there is also a considerable shift in the location of the nulls. The latter has serious system implications upon the overall performance enhancement since the degree of interference suppression will be severely impaired.

RF power amplifier linearization is a classic problem to wireless system designers. The feed forward linearization technique was considered by the consortium to be the most suitable approach for adaptive antenna applications. This is mainly because of the high degree of linearity attainable, broad frequency bandwidth, and unconditional stability [22]. The feedforward amplifier operates by comparing the distorted main amplifier output with an undistorted reference signal; the error signal generated is suitably combined with the main amplifier output such that the distortions are canceled. Eight amplifiers based on this architecture [23] were built for the TSUNAMI testbed system. Each module includes an IQ upconverter and fully adaptive control (using a TMS320C50 DSP — digital signaling processor — card) of the amplitude and phase control in the main amplifier signal path, and produces an output where the intermodulation products can be kept below –50 dBc (this approach can achieve spurious levels below –80 dBc using multiple adaptive loops). In addition, the use of linear power amplifier technology will also support the deployment of multiple-carrier base station architectures alongside adaptive antenna signal processing. This is important since SDMA operation cannot always be maintained due to the spatial location of the users; thus, handover to the FDMA domain is necessary.

Antenna Array Technology

The performance enhancement attainable with an adaptive antenna system depends heavily on the array geometry. In particular, the array geometry should be matched to the spatial characteristics of the radio environment. In rural operational environments the angular spreading is low, and received signals tend to have well-defined directions of arrival. For indoor and microcellular scenarios the angular spreading is high, and signals may no longer have well-defined directions of arrival. The choice of array topology (as well as the control algorithms) should reflect these differences in the signal environment. Thus, no single antenna architecture will provide an optimum solution for all environments. In order to test a variety of situations, three different antenna arrays were constructed for use in the TSUNAMI field trials [24]: linear, planar, and circular patch arrays with adjustable interelement spacing. Two different antenna element designs with circular microstrip patches, which include a parasitic patch in an upper layer, were also built for the trials. These antenna elements offered extremely wide bandwidths for patch technology, making them appropriate for UMTS deployment.

Spatial Propagation Trials

The influence of the physical environment on the perceived radiation pattern was one of the several aspects studied during the propagation measurement campaigns [25]. It was observed that the mean directional information of a moving user is much more slowly varying than the instantaneous angular fading. This can be exploited by algorithms that operate on the downlink based on uplink estimation. Furthermore, only in open rural areas could a 20 dB sidelobe pattern be supported from an antenna array. In cluttered environments where the perceived sidelobe levels are higher than the free space levels, the interference levels will be higher than expected by free space patterns [25–27].

The reduction in delay spread obtained by using the directional properties of adaptive antennas was also measured during the propagation campaign. In some rural environments a 60-fold reduction in delay spread was observed using a 5° beamwidth array. Nevertheless, the general trend was that delay spread is reduced by a factor of 2–3 in most scenarios, and up to an order of magnitude when strong and angular distinct reflections are present. It was also seen that the use of narrow beams also tends to increase the polarization purity [27].

It is well known that the more the environment scatters the energy observed at the base station site, the smaller the correlation coefficients between antenna elements. The TSUNAMI experiments revealed the familiar trend of decreasing correlation with spacing, but showed a difference between directional and omnidirectional elements for the same array size [27]. This effect can be interpreted as the effect of the local scatterers around and behind the array. This is eliminated by the directional patterns of the elements, which only see the narrow spreading near the mobile, and thus exhibit higher correlation coefficients. These correlation coefficients specify the antenna element structure to be used for traditional diversity algorithms (e.g., maximum ratio combining); hence, larger arrays are needed when directional elements are employed for classical diversity combining.

Furthermore, in large cell deployments the mean directional information of a moving user was seen to be much more slowly varying than the instantaneous angular fading. This characteristic can be exploited in order to form beams on the downlink based on uplink channel estimation for spatial reference algorithms as demonstrated here, and thus also provide a possible solution for frequency-division duplex (FDD) systems.

Adaptive Algorithms for Beamforming

The acquisition and tracking of a moving user is one of the most critical aspects for the application of adaptive antenna processing to mobile communications. Spatial reference beamforming techniques were considered to be the most suitable solution for large cell systems and were also most appropriate for the TSUNAMI demonstrator, where the modulation and demodulation methods are relatively simple. This technique mainly consists of estimating the angles of arrival of multiple users on the uplink (mobile to base station) and then using this information to allocate different beam patterns in order to support SDMA operation for both the up- and downlinks. In large cell scenarios, the application of these algorithms for tracking small changes of the directions of arrival (DOAs) becomes a computationally expensive task, and thus new computationally efficient algorithms have to be developed for DOA estimation. With this in mind, a simple and computationally efficient DOA tracking algorithm was developed for the field trials. The algorithm deployed in the trials was a combination of DOA estimation with the MUSIC algorithm [28] and Kalman filtering [29–30]. The application of the Kalman filter is useful in large cell operational scenarios because "reasonable" trajectories of the users can be accurately modeled and thus provide tracking during link obstruction.

Temporal reference antenna control methods (Fig. 2 and [15, 16]) can theoretically approach optimum performance for any given antenna array deployment, and thus offer much better performance than the spatial methods under many condi-

tions. However, in order to use these methods, the following air interface requirements are essential:
- A proper temporal reference (e.g., the pseudonoise sequences in a CDMA system) is required in order for the necessary signal correlation.
- Time-division duplex (TDD) air interface protocols seem to be more preferable in order to ensure spatial and under some conditions temporal correlation between the up- and downlink radio channels. For current FDD systems like TACS, Global System for Mobile Communications (GSM), Digital Cellular Service at 1800 MHz (DCS1800), IS-54, and IS-95, the temporal domain processing performed in the uplink cannot be exploited directly in the downlink, since the channels are uncorrelated; hence, some sort of processing of the optimal weights calculated for the uplink should be performed.

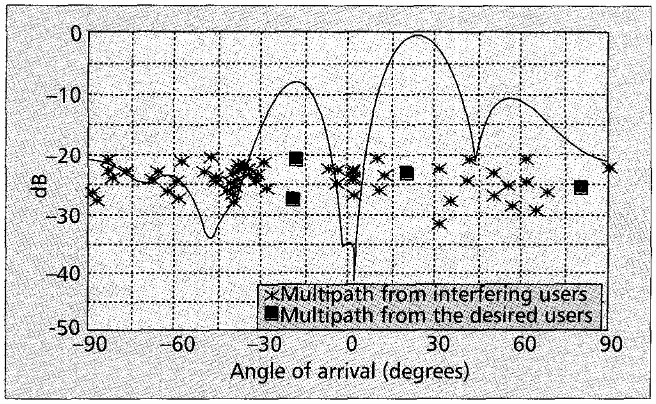
The spatial methods of control optimization do not place such requirements on the air interface; however, the major disadvantages of these methods include:
- Lower carrier-to-interference (C/I) enhancement when compared with the temporal methods.
- Minor inaccuracies in the transfer function of each of the antenna elements can lead to significant performance reduction. This problem is accentuated in FDD systems where the differences in the transfer function with frequency complicate the calibration process.
- Extra intracell handover capability is required to manage the problem of beam overlapping.

An additional complexity is the potential division of the air interface into a number of formats in order to cope with different services and cell applications. In this context, in order to mitigate the combined effects of intersymbol and co-channel interference, combined space and time processing can be employed [31].

Operational Benefit Analysis

Given that one of the objectives of the RACE TSUNAMI project was to investigate the potential deployment of adaptive antennas in third-generation mobile systems, analysis of a microcellular direct sequence CDMA (DS-CDMA) system employing adaptive antennas was also included. In [10] and [14] the ray tracing tool that was developed in [32] was used to obtain the spatial and temporal information necessary for a site-specific capacity analysis study. From this data the optimized radiation pattern was calculated in order to obtain the highest output signal-to-interference-plus-noise ratio over an 8-element 1/2 array using the Least Mean Squares (LMS), Normalized Least Mean Squares (NLMS), Recursive Least Squares (RLS), or Square Root Recursive Least Squares (SQRLS) algorithm to control the beamformer by applying temporal reference optimization via the embedded user code synchronizer. Figure 3 shows an example of the optimized radiation pattern with the SQRLS algorithm for a typical microcellular scenario with 15 interfering users, where the effect of mutual coupling between the antenna elements has also been considered. This process was repeated many times with a random deployment of users and interfering sources; each time the directivity of the optimum radiation pattern that was produced by the adaptive antenna was calculated, and from that the achieved capacity enhancement. The results indicate that at least a fivefold increase in the overall spectrum efficiency of the DS-CDMA network for microcellular operation can be achieved with adaptive antennas, thus further substantiating the benefits of this technology for UMTS type environments. Furthermore, benefit analysis of TDMA-based networks operating in large cells was considered, as reported in [33].

The benefits of adaptive antennas in a fully operational network have still yet to be appraised; thus, an evolutionary



■ **Figure 3.** *Optimized radiation pattern for a microcellular scenario with DS-CDMA.*

path was proposed by the consortium [34–36] in order to reduce the risk and also allow further optimization. Three phases were distinguished as outlined below:
- High-sensitivity reception (HSR) based on the adaptive array concept for uplink traffic. The signals received are spatially filtered, thereby increasing the sensitivity of the system as a function of the angular spectrum of the received signal. The principal advantage is that weak signals from the outskirts of the cell can now be received, thereby increasing the range covered by a base station. Here, the downlink beamforming is not implemented; however, in order to balance the link budgets an increase of downlink transmit power will be necessary.
- Spatial filtering for interference reduction (SFIR) exploits the spatial capabilities of adaptive antennas in both the up- and downlink directions. In addition to the increased range, the "customized" narrow beam to the mobile drastically reduces the interference generated by the base station and received by neighboring base stations. The limits imposed by self interference on the cell planning of a mobile communication system are thus considerably improved.
- SDMA embodies all the features described above. The spatial filtering in the up- and downlinks is now employed to support multiple users on the same frequency and time slot based solely on their spatial characteristics. In addition to the improvements in range and reduction of interference, such a system yields a direct capacity increase with corresponding significant impact on spectrum efficiency, as described earlier.

Field Trial Demonstration of SDMA

Testbed Description

A major goal of the RACE TSUNAMI project was to provide a field trial demonstration of both receive and transmit digital beamforming supporting SDMA user access; *proof of concept*. The Digital European Cordless Telecommunications (DECT) radio standard was selected as the operational wireless bearer since it could be readily integrated with the adaptive antenna platform, and furthermore can operate in an isolated radio cell mode, thus allowing networking aspects (e.g., handover) to be addressed at a later phase. The testbed hardware consisted of an eight-channel system employing a patch antenna array which could be deployed in various configurations and eight independent linear up- and downconversion chains which transform the signals to quadrature baseband (Figs. 4 and 5). The baseband system provides two independent bidirectional wideband beamformer channels to the DECT radio system. The digital beamforming cards were based on two DBF1108 chips developed from ERA Technology [37], each providing 32 million complex operations/s processing rate and 8-bit complex data,

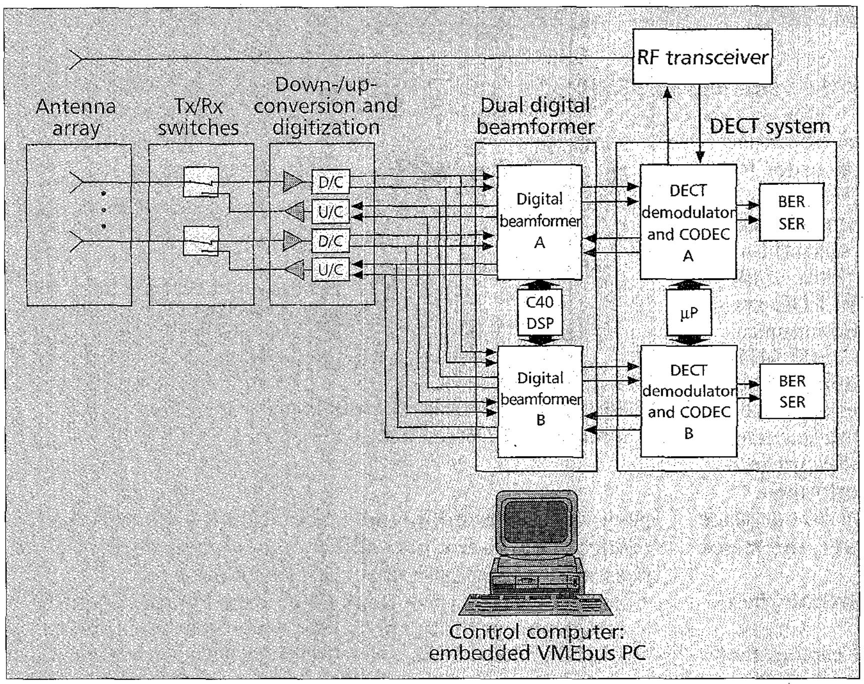


Figure 4. *RACE TSUNAMI testbed architecture.*

11-bit complex weighting coefficients (Fig. 6). The two DECT radio subsystems were designed such that each operated only on a single fixed frequency and time slot. The radios were also capable of supporting both speech and channel quality assessment measurements (received signal strength, bit and slot error rates) in order to provide a quality assessment of SDMA operation.

In order to compensate for mismatches and component drift within the multiple analog signal paths, a calibration system was employed. Calibration is required for DBF systems where each channel contains a complete transceiver, each of which must be amplitude- and phase-matched over the entire signal bandwidth. Any differences will preclude precise pattern control and will decrease the ultimate performance achieved with this technology. Receive calibration was achieved using a multiport carrier injection method with known amplitude and phase characteristics at the input of the receive path. The system contains a ganged automatic gain control (AGC) providing some 40 dB of control, and hence the calibration must be repeated for each gain setting since the element mismatch varies at different gain settings. Transmit calibration was performed by using the receiver to assess the performance of the transmit chain. Here, the multiple calibrated receiver ports were excited with the signals from the testbed transmit chain in order to provide transmit port calibration.

Two SDMA channels were supported on two independent DSPs, thus enabling the trial system to establish two links within the same time slot and frequency channel of DECT air interface through the spatial domain. In addition to real-time beamforming operation speech mode, the beamforming system also had 16 Mbytes dynamic random access memory (DRAM) for data logging for post processing applications. A PC-based controller with aVME bus interface was used to initiate the beamforming algorithms, enable the measurements, and finally read the stored data out of the system.

For the SDMA tests the MUSIC algorithm was used as the basic spatial reference algorithm. Each iteration of the adaptive algorithm consisted of three steps:

- Estimate the number of signals and directions of arrival using the MUSIC algorithm (strongest ray from each user).
- Apply the DOAs to the tracking algorithm.
- Synthesize beams for the users.

Field Trial Results

A large amount of data (in excess of 2 Gbytes) containing on-line beamforming results with different array processing algorithms and raw data from the eight antenna elements was collected from both outdoor and indoor environments. The field trial sites included the following locations:

- Urban, Leatherhead (U.K.)
- Urban, Kiel (Germany)
- Indoor, Sophienhof (Germany)
- Rural, Aalborg (Denmark)
- Urban and indoor, Bristol (U.K.)

The results presented here are from the trials performed in Bristol. The area is a typical outdoor urban environment adjacent to the Engineering Faculty building. The base station array was a $\lambda/2$ linear deployment at a height of ~30 m above ground level. In the first test scenario, the users start from points 1 and 2, as shown in Fig. 7. During the test they initially move at walking pace toward each other up to a point where their angular separation is almost 15° as seen from the base station; here they stop and return to their original positions. In Fig. 8a the tracked DOAs are given, illustrating the ability of the spatial reference algorithm to track the users. It is well known that the user resolution which can be achieved using the MUSIC algorithm is much better than the main beam width of the antenna array. However, the minimum user separation supported in the field trials was limited to about the 3 dB beam width of the array, mainly due to the difficulties associated with the synthesis of sharp nulls near the main beam in the SDMA patterns. The linear array used in these experiments had approximately 13° 3 dB beamwidth. Figure 8b shows the response of the beamformer in terms of the ideal produced radiation pattern for a midpoint of the route. Note here that there are two beams (one for each user), and that the peak of the beam which tracks user 1 corresponds to a null in the beam for user 2, and vice versa. This is a critical aspect of the beam control in order to provide the necessary C/I isolation.

Figure 9 contains the measured bit error rates (BERs) of the four independent channels (uplink-downlink for both SDMA users). Most of the time the BER is better than 10^{-3}, which is an

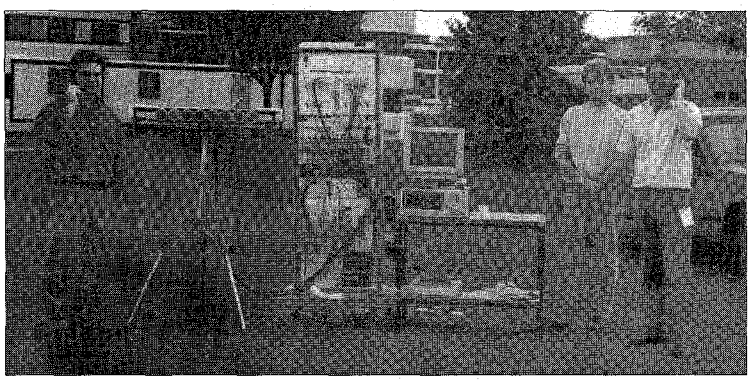
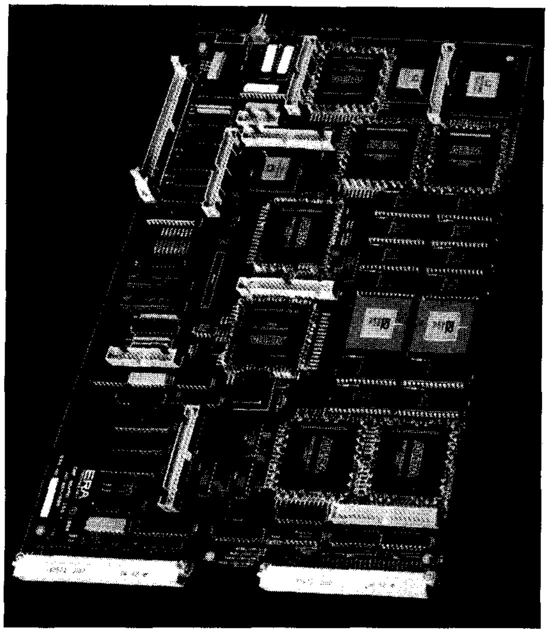
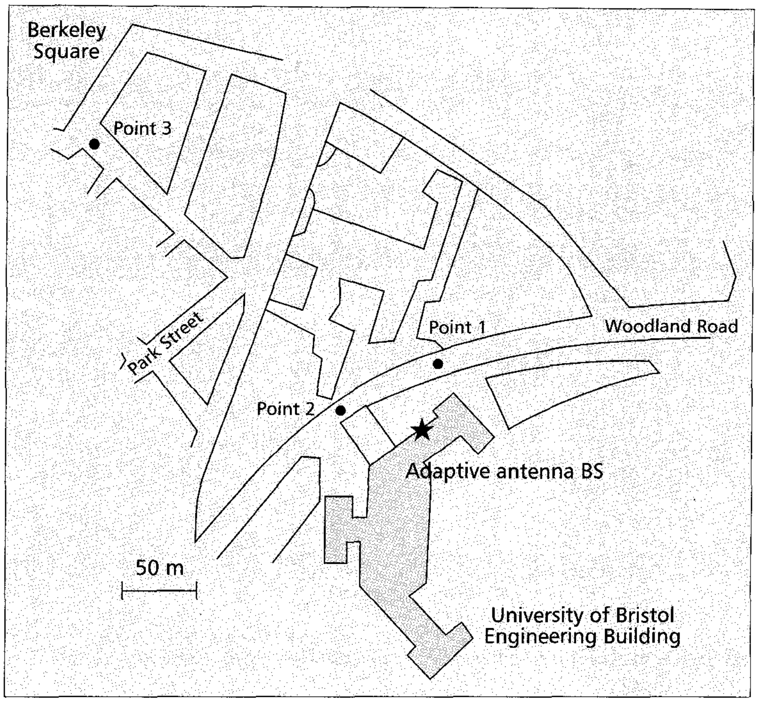


Figure 5. *RACE TSUNAMI testbed.*



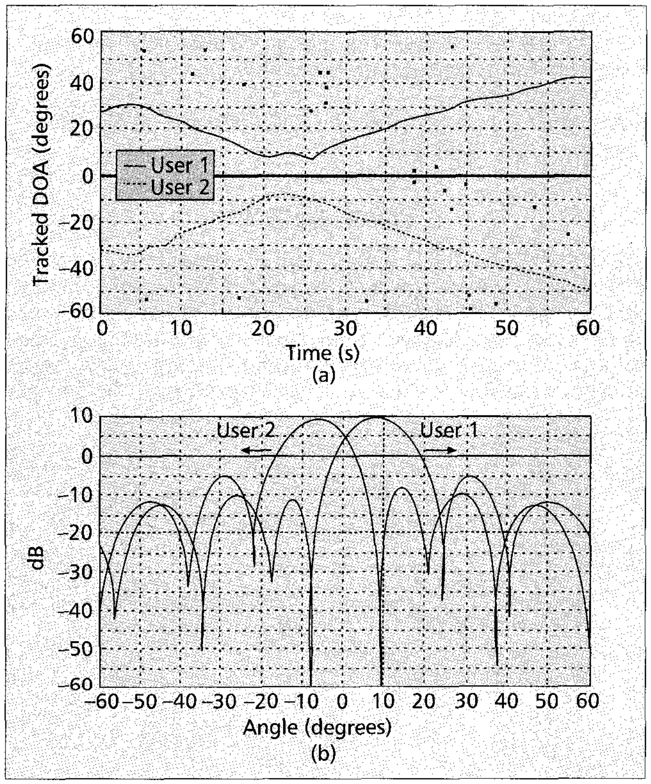
■ **Figure 6.** *DBF card.*



■ **Figure 7.** *Map of the area of the field trials.*

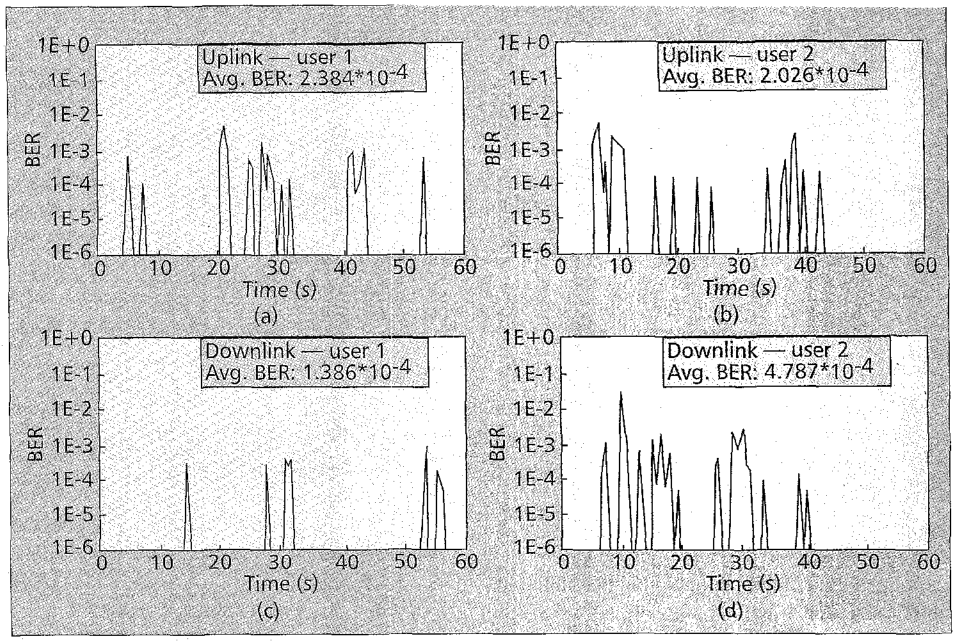
impressive demonstration of the SDMA capability of the TSUNAMI system. It should be noted that the spurious peaks shown in the BER figures are because there are some bad slots during the entire experiment, which are due to a problem of interference caused by other sources within the prototype base station (e.g., transmitter gating). From Fig. 10 an improvement of more than 8 dB in the received power level with the beamformer can be seen when compared with the single-element case.

In Figs. 11 and 12 results for the tracked DOAs from two other operational scenarios in Bristol are shown. In Fig. 11 the routes of the two users cross approximately at the array boresight. It can be seen that the spatial reference algorithm can track the two users, apart from the section where the beams overlap. Here, the tracking algorithm cannot spatially separate the users and thus produces an erroneous response, as can be seen for the tracked DOA between 28–42 s for user 2. This can be explained on the basis that the tracking algorithm has an estimate of the position and velocity of each source; that is, it knows where each source should be next, assuming no instantaneous changes in direction or velocity; hence, if it does not calculate a raw DOA estimate within a predefined window, it ignores this raw DOA. In this case the algorithm predicts where the source should be from the last DOA estimate and the source velocity. This approach works perfectly for user 1 during crossing, but loses the track for user 2. Meanwhile, the response from the MUSIC algorithm, in terms of the raw DOAs for user 2, recovers when the sources move sufficiently apart (37 s), but the tracking algorithm now estimates that user 2 should be between 40° and 20°; thus, this prediction is ignored. However, at t = 42 s the raw DOAs are within the threshold range of the track of user 2, so it interprets them as new position estimates and the tracking is re-established. It should be noted that it is not a requirement for the adaptive antenna to be able to separate spatially overlapping users. One possible way to cope with such problems is to make use of the handover mechanism.



■ **Figure 8.** *a) Tracked DOAs; b) a snapshot of the idealized radiation patterns at* t = *25 s.*

Figure 12 shows results for the scenario where user 2 starts from point 1 shown in the map in Fig. 7, and moves toward point 2, while user 1 is standing at point 3. This test was chosen in order to show the capability of the adaptive antenna to cope with a near–far scenario, since the distance between the two users is about 250 m. It can be seen that the adaptive antenna performs well in terms of the tracked DOAs and that, as expected, problems start to emerge when the angular separation of the users is less than the 3 dB beamwidth of the antenna array (after t = 42 s), although the tracking algorithm has successfully produced an approximate track for user 2. It is important to note that the benefits of spatial separation are only available post-beamforming; thus, the multiple analog downconverters are subject to high variability in the instantaneous dynamic range. From the BER results it can be seen



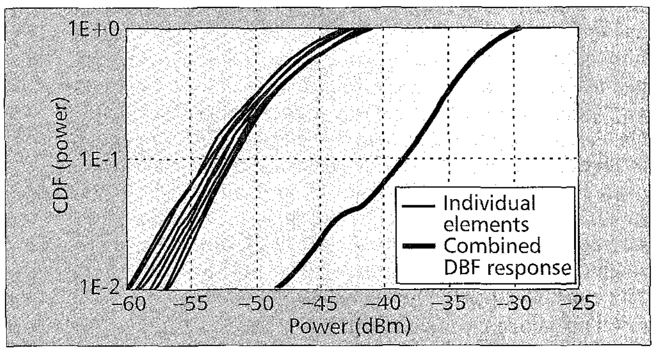
■ **Figure 9.** *Uplink BER: a) user 1, uplink; b) user 2, uplink; c) user 1, downlink; d) user 2, downlink.*

Commission of the European Community (CEC) has funded a follow-on project under ACTS, TSUNAMI II. The DECT system employed in the RACE TSUNAMI did not allow detailed evaluation of network aspects associated with adaptive antenna techniques. This is the main goal for the TSUNAMI II project. Here, within the family of GSM derivatives, it was decided to use the DCS1800 standard because it is arguably closer to the third generation than GSM; but most important, it utilizes very similar frequency bands to UMTS/IMT2000 proposals. The TSUNAMI II field trial will take place using the Orange PCS testbed facility in Bristol, United Kingdom. Here, the trial will exercise the system in order to fully identify the performance of the adaptive antenna relative to

that both users could be supported with acceptable link quality for the entire experiment apart from when they were spatially overlapping.

Current Activities in Europe on Adaptive Antennas

In order to further develop adaptive antenna technologies for third-generation systems and also ensure that the success of the RACE TSUNAMI project is built on, rather than lost, the



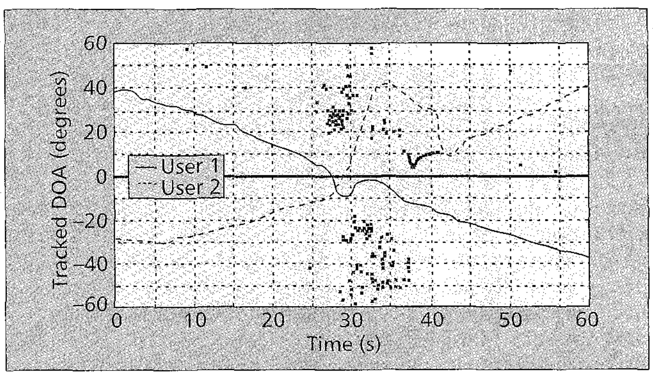
■ **Figure 10.** *Cumulative distribution function of the power of each antenna element and of the power at the output of the beamformer.*

the performance of the existing trisectored DCS1800 base stations. Of particular interest to network operators are parameters that impact cell sizing, fading protection, and, most important, spectral efficiency gains using adaptive antenna technology. These will be assessed both analytically and via field trial experimentation. Furthermore, the consortium will also consider and provide:

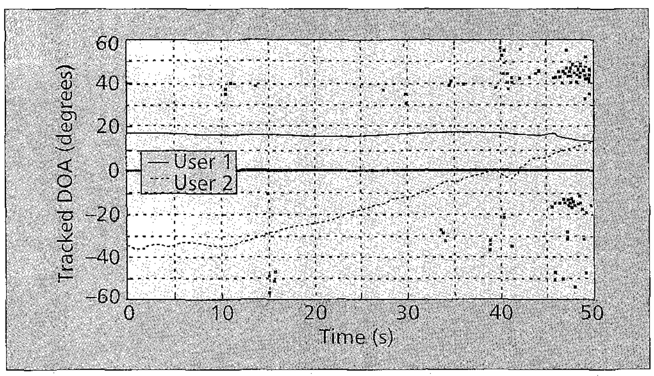
- Identification of the optimum beamforming algorithms and antenna array geometries
- System-level performance predictions
- Standards proposal for full integration of the adaptive antennas to the UMTS system
- Joint multi-user detection techniques with adaptive antennas
- Spatial and temporal radio channel characteristics for UMTS services
- Microcellular optimization study for adaptive antennas
- Microcellular field trials

Conclusions

A consequence of the phenomenal expansion of mobile telecommunications systems around the world is the fact that networks are rapidly running out of system capacity and electromagnetic spectrum. Future systems like UMTS promise to provide higher-value services, and this inevitably means higher data rates and more capacity problems. In this sce-



■ **Figure 11.** *Tracked DOAs for the scenario of crossing users.*



■ **Figure 12.** *Tracked DOAs for the "near–far" scenario.*

nario, new technologies like adaptive antennas could fulfill the requirement for increased spectrum efficiency.

So it is beyond doubt that Adaptive Antennas are needed in future mobile systems; but can they perform to expectation?

Clearly the RACE TSUNAMI consortium demonstrated the viability of adaptive antennas to provide the increased capacity needed for UMTS via SDMA. Now, through the follow-on activity under ACTS, the consortium will take this technology and the associated standards closer to full network deployment.

ACKNOWLEDGMENTS

The authors wish to thank the CEC for funding both the RACE and ACTS TSUNAMI projects. In addition, we would like to thank all the partners in RACE TSUNAMI (ERA Tech. Ltd., Hagenuk GmbH, Alcatel Sel, Detycom, Univ. of Aalborg, Univ. Politecnica de Catalunya) for their contributions to this activity. Special thanks are due to R. Arnott of ERA Tech. Ltd. and R. Wilkinson, R. Davies, H. Xue, C. Simmonds of Bristol University. Finally, we wish to acknowledge the support of our partners in the ACTS TSUNAMI II project.

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