Intelligent Antenna Solutions for UMTS: Algorithms and Simulation Results

Pantelis Monogioudis, Keith Conner, Deepak Das, Sridhar Gollamudi, Jung Ah C. Lee, Aris L. Moustakas, Shirish Nagaraj, Anil M. Rao, Robert A. Soni, and Yifei Yuan, Lucent Technologies

ABSTRACT

This article outlines the development of intelligent antenna (IA) solutions for UMTS, a third-generation W-CDMA system. Since the selection of an antenna configuration paired with realizable uplink/downlink algorithms that can satisfy all operating environments is a broad task, this article focuses on cost-effective antenna arrays for macrocells. Algorithms that exploit the antenna configurations and act at both the physical and MAC layers are highlighted and supported by simulation results. Two solutions stand out for UMTS: a universal beamforming algorithm that unifies user-specific and fixed beamforming under one framework, and multibeam scheduling (MBS) that significantly increases downlink packet data throughput using the concept of code reuse in conjunction with beamforming. The article summarizes the critical issues that were faced in the development of an IA solution capable of delivering the theoretically promised benefits to end users.

INTRODUCTION

The use of multi-antenna arrays in wireless communications coupled with “intelligent” processing algorithms of their signals has recently been dubbed intelligent antennas (IAs). IAs continue to be a hot topic of research and development in an effort to boost the performance of wireless communications and provide competitive advantage to equipment vendors and operators. In this article, we focus on Universal Mobile Telecommunications System (UMTS) frequency-division duplex (FDD) standards (R99, R4, and R5). Before addressing UMTS-specific issues, the concept of beamforming is explained next.

As shown in Fig. 1 the mobile, in most environments, may be modeled as embedded in a cluster of local scatterers (cluster 0) [1]; for example, the body of the user, the ground, or nearby cars. When the base station antennas are elevated, the base station may be modeled as being far away from scatterers. The signal originating from the mobile station or user equipment (UE) transmitter is reflected by clusters in the far field of the base station antennas (clusters 1 and 2). Associated with each reflection is a time delayed and phase shifted version of the transmit signal that arrives at the mobile via a different direction of arrival (DoA). The locations of scatterers are assumed to be identical between uplink and downlink. This symmetry is fundamental to the operation of IA in FDD systems.

When multiple antenna elements at the base station are closely spaced, the received signals from a particular mobile are correlated at the base station antennas for macrocells. Thus, the base station can estimate long-term statistics — more specifically, second order moments such as the correlation matrix of the channel. These estimates can be used to calculate weights that satisfy an optimality criterion (e.g., minimizing the uncoded symbol error rate seen by the mobile). When these weights multiply the transmitted signal, the signals arrive co-phased at the terminal location.

<table>
<thead>
<tr>
<th>Antenna configuration</th>
<th>Fig.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1V</td>
<td>(a)</td>
<td>1 column with vertical polarization (V-pol)</td>
</tr>
<tr>
<td>ULA-2V</td>
<td>(b)</td>
<td>2 closely spaced V-pol columns</td>
</tr>
<tr>
<td>ULA-4V</td>
<td>(c)</td>
<td>4 V-pol columns</td>
</tr>
<tr>
<td>DIV-1X</td>
<td>(d)</td>
<td>1 column with dual-slant polarization (X-pol)</td>
</tr>
<tr>
<td>CLA-2X</td>
<td>(e)</td>
<td>2 closely spaced X-pol columns</td>
</tr>
<tr>
<td>CLA-3X</td>
<td>(f)</td>
<td>1 X-pol middle column with two closely spaced columns of +45-pol</td>
</tr>
<tr>
<td>BM-4X</td>
<td>(g)</td>
<td>4 X-pol columns with dual Butler matrix</td>
</tr>
<tr>
<td>DIV-2X</td>
<td>(h)</td>
<td>2 widely spaced X-pol columns</td>
</tr>
</tbody>
</table>

Table 1. An explanation of base station antenna configurations.
resulting in immediate signal-to-interference ratio (SIR) benefits. The SIR benefits translate to reduced power consumption at the base station for power-controlled channels. For shared channels, the SIR benefits result in improved throughput and delay metrics.

Figure 2 shows the antenna configurations a base station constrained by 12 radio frequency (RF) cables. Twelve RF cables can support 4 antennas per sector for a 3-sector base station and 2 antennas per sector for a 6-sector base station. Each configuration is explained in Table 1.

Only IA solutions that can be implemented in cost-effective baseband processing are considered in this article. “Applique” analog solutions such as BM-4X are not considered. Since DIV-2X is most suitable in the downlink for BLAST and BLAST is not being considered for inclusion in UMTS until after Release 5, BLAST is not considered in this article. For mobile terminals, antenna configurations are related to terminal types.

Voice terminals are assumed to have one or two antennas, and high-speed packet-data-oriented terminals — such as those serving the UMTS high-speed downlink packet access (HSDPA) markets — are assumed to have more than two antennas (as allowed by the form factor and the cost of materials budget).

**STANDARDS SUPPORT OF INTELLIGENT ANTENNAS**

The third-generation wideband code-division multiple access (W-CDMA) standard drafted in the Third Generation Partnership Project (3GPP) has been designed to allow multiple antenna configurations in both the base station and the mobile. The specifications support IA via two primary means. First, pilot channels are defined to provide reference signals that can help the estimation and detection functions of the receiver. Second, protocols are defined to handle measurements necessary for allocating pilot channels, configuring radio links, and transferring measurements so that radio resources within the access network can be allocated optimally.

In the uplink, all 3G systems employ a dedicated pilot that is multiplexed with the data channel. Although the uplink pilot can be discontinued for short periods of time, the long-term second order statistics estimated at the base station are relatively unaffected. The uplink pilot adds coherent gain and significantly improves not only the estimation of spatial correlation across the antenna array but also the estimation of multipath delay.

In the downlink, three pilot channels have been defined:

- Primary common pilot channel (P-CPICH)
- Secondary common pilot channel (S-CPICH)
- DPCCH PILOT (DPILOT) (known as dedicated pilot)

In many situations, the IA solution is proprietary to the base station vendor, and the mobile is, in principle, unaware of beamforming. Furthermore, not all physical channels can be beamformed. For example, users that do not have an established dedicated connection cannot be beamformed.

The P-CPICH allows a terminal (without an established dedicated connection) to select the best sector and decode the broadcast informa-
Table 2: Power-delay profile (PDP) mixture.

<table>
<thead>
<tr>
<th>PDP</th>
<th>Relative power to first path (dB)</th>
<th>Relative delay (ns)</th>
<th>Velocity (km/h)</th>
<th>Occurrence prob (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian A</td>
<td>[0.0, –0.9, –4.9, –8.0, –7.8]</td>
<td>10.0</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Pedestrian B</td>
<td>[0.0, –9.0, –10.0, –15.0]</td>
<td>30.0</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Vehicular A</td>
<td>[0.0, –10.0, –12.8, –10.0, –15.0]</td>
<td>100.0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Vehicular B</td>
<td>[0.0, –2.5, –12.8, –10.0, –15.0]</td>
<td>120.0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Single path</td>
<td>[0.0]</td>
<td>3.0</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Fixed beam pattern for ULA-4V. Solid lines are the fixed beams, and the dotted line is the per-column antenna pattern.

Simulation Methodology

Realistic simulation models that capture not only the performance of the physical layer but also the performance of the MAC and radio resource control layers are necessary for developing IA algorithms and determining antenna configurations that optimize system capacity. The Wireless Algorithm Validation Environment (WAVE) is an internal Lucent simulation tool, developed to support performance studies for a variety of radio interfaces. Key components of the adopted simulation methodology are the concept of a virtual decoder and the elaborate spatial channel model described next.

The Virtual Decoder

Figure 4 depicts a multilayered cloverleaf cell layout simulation snapshot. Within this environment the air interface abstractions of both the link and system levels are accessible, denoted co-simulation. Co-simulation provides verification of the system-level abstraction using the link-level capabilities and vice versa. A link-level user is simulated at an oversampled chip rate. At the system level, multiple users are simulated at a rate of 1 sample/time slot.² At this rate the instantaneous SIR (at the reference point shown in Fig. 5) is calculated, assuming a block-fading model over a time slot. The reference point of the measurement is at the input to the virtual decoder (VD), after despreading, channel compensation, and spatiotemporal combining or equalization.

A VD uses a metric extracted from the vector of SIR measurements and implements the mapping from this metric to a block error decision (cyclic redundancy check, CRC, result). The CRC decision drives the link adaptation loops such as outer-loop power control for dedicated channel communications and rate control for high-speed packet data over shared channel communications. The designed VD metric proves to be very accurate for both convolutional and turbo coded transport channels. A single user simulated at either 1 sample/slot or 1 sample/chip exhibits identical statistical performance. This instantaneous value interface (IVI)

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¹ For most practical cases it is not transmitted using a single element but shaped before being transmitted by the antenna array.

² One time-slot = 0.667 ms for UMTS.
methodology allows flexibility in determining realistic capacity achieving criteria. For example, capacity can now be ascertained from system-level quality of service (QoS) statistics rather than exclusive use of transmit power outage statistics or received noise rise.

**THE SPATIAL CHANNEL MODEL**

The channel model is a critical factor in determining the relative performance of IA techniques. The extent to which beamforming is effective is determined by the angular width of the incoming energy — the composite root mean square (RMS) angle spread. As shown in Fig. 1, typically each cluster has a different angle of arrival (AoA) at the base station. Thus, the AoA of each cluster is modeled as a random variable chosen from a Gaussian distribution with variance equal to the composite angle spread. Each cluster associated with a path has an inherent RMS angle spread of its own, which is assumed to be fixed at 5°. Shadow fading follows the Gudmunson model [3] — with decorrelation length of 50 m and inter-BS correlation of 0.5. These assumptions are a simplified set of those adopted by the 3GPP standards bodies [1]. In addition to the spatial structure of the channel, the temporal behavior of the channel, described by the delay spread, must be considered. This quantity characterizes the temporal width over which the incoming energy is distributed. Large delay spread can be exploited by the receiver to provide diversity gain. For the purposes of this article, we have used a discrete set of channel power-delay profiles (PDP) and a set of associated maximum Doppler frequencies. The PDP mixture is shown in Table 2.

**THE IA SOLUTION FOR DEDICATED AND CONNECTIONLESS CHANNELS**

This section presents simulated IA performance results for power controlled dedicated and common control channels. The most widespread service carried over dedicated channels for UMTS is adaptive multirate (AMR) coded voice and associated radio resource control signaling. In all cases, 12.2 kbps AMR and 3.4 kbps associated signaling were assumed with the latter exhibiting the same activity factor as the voice traffic — a worst case assumption in terms of power consumption. Out of the common control channels, the random access channel (RACH) provides the primary method for connectionless transport of both signaling as well as low to moderate offered loads of packet data traffic in the uplink. As such it is not closed-loop power controlled and represents, depending on the cell configuration, a significant source of uplink noise rise.

**UPLINK DEDICATED CHANNEL BEAMFORMING**

In the uplink, IA signal processing is done on a per path basis. Minimum mean squared error (MMSE) spatial combiners attempt to remove the spatially correlated interference. Practical MMSE algorithms are limited by the number of antennas and the Doppler frequency of the mobile of interest. This spatial processor is called a precombiner as it precedes the final temporal RAKE combining. A block diagram of this processing is shown in Fig. 6.

Practical BSs feature routing of received uplink signals to the baseband demodulator, (i.e., multipath searching is being performed over multiple sectors). The antenna interface block represents this routing function that presents to each MMSE precombiner only the antennas that correspond to the same sector. Two spatial correlation matrices are used to calculate the precombiner weights. The first matrix is the global correlation matrix, referenced at the antenna connectors. This matrix contains the spatial correlations of the total signal plus interference in the sector that result from CDMA transmissions. The second correlation matrix is user-specific, referenced at the output of the user despreader. The effects of channel estimation noise are reduced by averaging over relatively short periods of time. The weight vector for the MMSE precombiner is given by the principal eigenvector of the product of the inverse of the global correlation matrix and the user-specific correlation matrix. The complexity of the weight calculation can be reduced to an acceptable implementation cost. The RAKE combining process follows the application of the weight vector and combines the signals temporally into the final log-likelihood ratio metric used by the decoder.

The determination of the capacity limits in
the uplink are based on the following criteria:

- Noise rise limit: The noise rise averaged over one slot does not exceed 7 dB more than 1 percent of the time [4].
- QoS limit: The fraction of terminals in QoS outage (defined as the per-user outage [4]) is less than 5 percent.

The uplink capacity limits for voice are shown in Fig. 7. The following observations can be made:

- The CLA-2X antenna configuration which exploits receive diversity performs better than ULA-4V. Simulations show that the average noise rise of ULA-4V is about 0.3 dB higher than that of CLA-2X. Similarly, the fraction of mobiles in QoS outage is lower for the CLA-2X configuration.
- The six-sector BS with receive diversity provides a gain of 167 percent over that of a three-sector BS with receive diversity.

**RACH Channel Beamforming**

Enhancing the RACH preamble detection as well as message reception is more of a requirement than an option for IA-enhanced dedicated channels. The RACH preamble carries a pattern known to the receiver, called a signature, and the job of the detector is to acknowledge successful reception of the preamble, paving the way for further signaling exchange and final admission of the user to the network. Detection structures based on the generalized likelihood ratio test (GLRT) lead to detectors that work either on the principle of maximum eigenvalue of the received correlation matrix or by selecting the best beam out of a set of fixed beams. The generic RACH detector structure is shown in Fig. 8.

The signal flow diagram resembles the dedicated channel signal flow in the pre-whitening step, but the despreading part is implemented via code matched filters (CMFs) rather than serial correlators. The CMF span covers the maximum delay spread associated with the cell coverage determined by the link budget. Link-level simulation results that quantify the probability of missed detection are shown in Fig. 9.

The results indicate that searching over a finite set of beams (fixed beam detector) gives reasonably good results in a variety of spatial interference scenarios. Thus, a fixed beam detector can be a good trade-off against the maximum eigenvalue solution. The penalty of ULA over CLA configurations is less than 2 dB for the scenario presented. System-level results not presented in this article also indicate that the mobile station transmit power for the ULA-4V configuration is higher by less than 1 dB than that for the CLA-3X configuration, notably because the RACH has inherent retransmission diversity.

**Downlink Dedicated Channel Beamforming**

Uplink receiver processing is performed on a per path basis. This approach is affordable due to the inherent multipath diversity of spread spectrum signals and the capability of the receiver to estimate the uplink channel. In the downlink, the knowledge of the downlink channel is not
available at the BS transmitter (due, in part, to the difference between uplink and downlink carrier frequencies). Thus, the downlink transmitted signal weights account for the composite angle spread rather than the per-path angle spread. Two main categories of downlink beamforming algorithms are available:

- **User-specific beamforming (USBF):** Beams are formed for each individual user in the sector. If \( N_{\text{user}} \) mobiles have established a dedicated connection with the BS, \( N_{\text{user}} \) individual beams will be formed such that the selected optimality criterion is satisfied for each user independently.

- **Fixed beamforming (FxBF):** The base station transmits a number of fixed beams and allocates one of those beams to each user. Earlier we depicted a scenario with four beams per sector. Each beam is supported by an S-CPICH pilot.

**Universal User-Specific Beamforming**

Universal USBF (UUSBF) algorithms provide the benefits of USBF in a cell that provides S-CPICH pilots that traditionally are used in FxBF solutions. UUSBF has been developed and validated in WAVE.

The universal beamformer forms user-specific beams in the presence of a fixed beamforming network. If the network is configured to support S-CPICHs, which are transmitted with fixed beamforming weights, the users can be made to use one of the S-CPICHs as a phase reference for demodulating their signal. In this case, sending the users signals with the same fixed beamforming weights as their reference S-CPICH channel is straightforward, but entails loss of performance due to the mismatch between the fixed weights and the channel seen by that user.

Optimal UUSBF works on the principle that the phase reference is a known fixed beamforming weight vector, and thus calculates the best dedicated weights for each user, taking into account the fact that the mobile has no knowledge of any such beamforming being applied.

This beamformer utilizes the user-specific channel correlation matrix information from uplink measurements to steer the user’s signal in the direction of the mobile. The advantages of this approach over both FxBF and plain USBF with P-CPICH phase reference are multifold:

- For channels with small angle spread, the performance of this scheme is optimal in the sense that it achieves the best possible beamforming gain for the given number of antennas.
- The scheme is fair, in that all users get similar performance irrespective of their geographic location. In plain fixed beamforming systems, users stuck between beams can take a significant hit in performance.
- For larger angle spreads the performance approaches that of a pure FxBF system, making the system more robust to angle spread than one where the phase reference is P-CPICH.
- The scheme is robust to delays in signaling a change in phase reference. When a user moves from the coverage area of one beam to another, RRC layer signaling is involved to indicate to the mobile that it must change the phase reference to another S-CPICH ID. FxBF systems can be very sensitive to such delays, depending on the beam pat-
tern. UUSBF is much more robust to such delays.

- In an attempt to eliminate scalloping losses other solutions define many nonorthogonal beams per sector [5] or apply beam sweeping, a concept similar to phase sweep transmit diversity (PSTD).

UUSBF avoids the scalloping losses inherently, without the added complexity and cost associated with the other solutions. In addition, the optimal beam sweeping frequency for dedicated channels can differ significantly from the optimal frequency for shared channels, a problem in mixed traffic environments.

The computational complexity of this approach is comparable to that of USBF and is realizable in baseband. The performance of UUSBF is illustrated in Fig. 10 for a ULA-4V antenna configuration for a single user with a pedestrian A channel profile. For this illustration, the per-path or wideband angle spread is 2°, and the composite or narrowband angle spread is fixed at 10°. The required Tx $E_{c}/N_0$ is plotted as a function of AoA. FxBF gains follow the beam patterns exhibiting associated scalloping losses, whereas the UUSBF algorithm (that uses the best fixed beam as an S-CPICH phase reference) is able to maintain a 5.5 dB gain over the single antenna case over almost all AoAs.

The determination of the capacity limits for the downlink are based on the following criteria:

- Transmit power limit: The 10 min average transmit power does not exceed the amplification rating of 43 dBm.
- Overload limit: The average aggregate overload control (AOC) gain is greater than 0.95.
- QoS limit: The fraction of terminals in QoS outage (defined as the per-user outage in [4]) is less than 5 percent.

Figure 11 illustrates the downlink performance comparison of all multi-antenna techniques considered in this article. All cases shown refer to a single antenna at the mobile except the bar labeled 1V-k65 MRxD MMSE, which corresponds to the case of two antennas receive diversity at the mobile using MMSE combining:

- A three-sector cloverleaf layout with ULA-4V antennas is capable of achieving higher capacity than a six-sector layout with a DIV-1X antenna configuration by a margin of 38.50 percent, which is generically true irrespective of the beamforming algorithm or transmit diversity type.
- The ULA-4V fixed beam solution appears to be quite robust to per-path angle spread. The ULA-4V fixed beam solution provides a 90–100 percent improvement in capacity over the best performing algorithm with a traditional DIV-1X antenna configuration. Compared to the single transmit antenna, the ULA-4V fixed beam solution provides 175 percent improvement in capacity.
- The ULA-4V with UUSBF provides more than 200 percent increase in capacity gains over the baseline 1V-k65, while the application of USBF over the FxBF provided a gain of almost 30 percent.
- Although not evident by the results in Fig. 11, the performance of ULA-4V USBF with P-CPICH reference degrades significantly with increasing angle spread. However, use of the P-CPICH reference still outperforms a single transmit antenna since the beamformer algorithm will adaptively widen the beam based on uplink measurements.

**The IA Solution for High-Speed Downlink Shared Channels**

Many of the insights gained on the benefits of multi-antenna solutions for dedicated voice traffic do not directly carry over to the case of HSDSC data systems. This is primarily due to the scheduled nature of transmissions, whereby only one or a few users are selected for transmission at a time based on their instantaneous channel conditions. Such systems enjoy a rich source of diversity not found in dedicated channel systems, known as multi-user diversity. Multi-

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3 It is possible to simultaneously schedule more than one user at a time by code multiplexing. The number of code multiplexed users is limited to a maximum of 15.
user diversity refers to the increase in system throughput as the number of users is increased, due to the fact that the likelihood of the scheduled user experiencing a peak of the individual channel SIR distribution increases with the number of users in the system. Naturally, multi-user diversity is higher when the individual channel SIR distributions have large peaks. Mobiles send channel quality information (CQI) to the entity of the medium access control (MAC) layer that is responsible for scheduling and rate control, which are the two resource management functions of interest. CQI is a quantized function of SIR present in the antenna connector of the mobile and as such is a function of the channel quality. The MAC layer based on CQI and other side information is then able to trade off latency and data rate by scheduling users as close as possible to the time they would experience favorable channel quality. One other notable feature of the MAC layer for high-speed shared channels is Hybrid Automatic Repeat Request (HARQ)-based retransmission supported by a Stop and Wait protocol. HARQ implemented with asynchronous ph incremental ph redundancy (IR) significantly boosts the time diversity of the radio link and helps quicken recovery from erroneous transmissions without the delay penalties associated with ARQ Type I/II protocols. The power allocated to the shared channel is determined by radio access network controller algorithms that determine the priority between power controlled dedicated channels and shared channels. For best effort HSDPA services sharing the same carrier with delay-intolerant real-time services such as circuit-switched voice, the power assigned to HSDPA is that left over from dedicated and common channels such as P-CPICH. Before presenting the impact of IA on HSDPA performance, Table 3 reviews the HSDPA configuration parameters used in the simulations. All aspects of HSDPA at the MAC and physical layers as detailed in the 3GPP specifications have been modeled.

**BASELINE PERFORMANCE**

Figure 12 shows the average packet call throughput averaged over all mobiles in the sector and over all the independent simulation runs. In the case of HTTP traffic, the average packet call throughput drops from around 170 kb/s to roughly 25 kb/s as the number of users instantiated in the cell is increased from 10 to 80. Sector service throughput results are plotted against the number of instantiated users with HTTP traffic in Fig. 13. The cell service throughput increases with the number of users, a behavior called multi-user diversity. After it peaks it will decline with further increase of the number of users. Multi-user diversity benefits are evident up to the point where there is a critical number of users in the sector in that the scheduler can always identify users with favorable channel conditions and empty their buffers as it has plenty of power to carry out viable transmissions in the majority of user locations. The subsequent decrease in service throughput is due to the decrease in available transmit power as more connected users consume more power to maintain the links over the required power-controlled physical signaling channels.

During these simulations we also monitor the delays within the buffer at the input of the scheduler and the retransmission buffer. It can be seen that the retransmission buffer delays are on the order of a few milliseconds. In contrast, the buffering at the input of the scheduler incurs delays on the order of several hundreds to thousands of milliseconds. This shows that the vast majority of delays in HSDPA are due to the waiting time prior to scheduling.

The results up to now are all based on Rake receivers at the terminals. Due to severe multipath, in many instances equalizer-based receivers are required to minimize ISI. The equalizer can significantly reduce same cell and colored other cell interference in multipath channels.
THE ROLE OF TRANSMIT DIVERSITY

Transmit diversity techniques such as STTD, CLTD, and PSTD alter the individual SNR distribution in a way that makes it more unlikely for a user to experience deep fades or high peaks. This has a very desirable effect in dedicated channels due to the fact that the user is not stuck in a deep fade very often. However, due to multi-user diversity in scheduled shared data systems, it is the peaks of the distribution, not the fades, that largely determine the total system performance. Moreover, in 3G shared data systems such as HSDPA, other sources of diversity are available in the form of multipath propagation and HARQ retransmissions, in addition to multi-user diversity. Therefore, transmit diversity techniques do not provide as much benefit in shared data systems as in dedicated channels. Transmit diversity techniques based on space-time coding, such as STTD, result in the average of the SNR distribution being the same as with single antenna transmission. However, STTD shorts the tails of the distribution. With a sufficiently large number of users, this can actually degrade performance relative to single antenna transmission due to the reasons mentioned above. Closed-loop transmit diversity techniques that are based on co-phasing the multiple antenna signals, such as CLTD, also shorten the tails of the distribution. However, they also increase the average SNR; thus, they offer some gain over single antenna transmission. Figure 14 shows the beneficial effect of CLTD on average service throughput for Rake receivers.

The use of CLTD causes some side effects. The power allocated in shared packet data channels is high enough that the common pilot SIR is affected from time slot to time slot. This results in multipath channels in what is called CQI contamination, a phenomenon that can also be attributed to CLTD operation in nearby BSs. As a result of this contamination, an increased number of HARQ retransmissions have been observed that affects QoS. In addition, CLTD can also affect the equalizer gain and/or marginalize their benefit. The explanation of these losses has to do with equalizer training and are outside the scope of this article.

Finally, although PSTD does not necessarily shorten the tails of the SNR distribution, while increasing its average, the existence of multi-user diversity in addition to fading erodes any possible gains of its use. The results of the application of PSTD are summarized in Fig. 15. Two antenna configurations have been employed, DIV-1X and ULA-2V. In the first case, there are essentially no gains even with very small Doppler fading (3 km/h). With ULA-2V, the setup resembles a rotating beam. Interestingly, in this case the cell service throughput is lowered for a large number of users, due to the fact that there is a significant number of users away from the center of the beam, resulting in reduced beamforming gains and higher delays. Similar results have been seen elsewhere [6].

CODE REUSE WITH BEAMFORMING ANTENNA CONFIGURATIONS

It is clear that a desirable multiple antenna transmission scheme should increase the average SNR and not decrease SNR peaks. Beamforming with closely spaced antennas is one technique that increases the average SNR without
changing the shape of the distribution, thus not shortening the tails. Consequently, beamforming provides a larger increase in system throughput than transmit diversity techniques.

Although the SNR improvement due to beamforming results in throughput enhancement, a more dramatic benefit comes from the fact that beamforming enables simultaneously scheduled users, separated spatially using beams, to share the same bandwidth (or codes) and split the available power. This is due to the fact that while throughput increases logarithmically with SNR, it increases linearly with bandwidth. We can understand this with the help of the following idealized example. If the symbol rate is \( R_s \) symbols/s and there are \( W \) codes available, a user whose instantaneous SNR is \( \rho \) with a single antenna transmission can achieve an instantaneous rate of roughly \( W R_s \log (1 + \rho) \) b/s. The same user can roughly achieve an instantaneous rate of \( W R_s \log (1 + N \rho) \) with the help of beamforming with \( N \) closely spaced antennas. If two such users split the available power in half and are spatially separated using beams formed with \( N \) transmit antennas, the combined throughput they can achieve is \( 2WR_s \log (1 + N\rho/2) \), which is larger than the one-user throughput with beamforming. We shall refer to the technique of scheduling multiple spatially separated users with code reuse as multibeam scheduling (MBS).

In a practical system, gains from MBS are tempered by interference between beams due to overlapping beam patterns and angle spread seen at the BS. Our MBS solution for HSDPA involves optimal scheduling of users based on priority, channel quality and spatial location, and optimal power, bandwidth, and beam allocation to the scheduled users.

In order to evaluate the improvement in air interface performance due to beamforming without constraints imposed by traffic models, the simulation results presented next assume full buffers at the MACs of all active users. Figure 16 shows the average cell service throughput for different numbers of users in the cell and different antenna technologies. All quantities, (cell throughput and number of users) are scaled to refer to the area of one cell in a three-cell cellular layout.

Figure 16 shows that fixed beamforming provides 30–35 percent improvement in cell service throughput over that of single antenna transmission. Also, a narrower element pattern with 65° beamwidth provides higher throughput than a 90° pattern in a three-cell layout. The throughput per unit area from a six-cell layout with one transmit antenna is slightly less than two times that from a three-cell layout with one transmit antenna. This can be explained as follows: while antenna gain of the 33° pattern used in the six-cell layout roughly compensates for the 3 dB decrease in the transmit power per cell, there is complete reuse of bandwidth between the two cells in a six-cell layout that correspond to one cell in the three-cell layout. Gains for individual users can be inferred from Fig. 17, which shows the probability distribution of user-perceived service throughput using different antenna technologies.

The more striking result is that when MBS with code reuse is used in a three-cell layout, it exploits code reuse without need for a six-cell deployment, and provides 80 percent improvement in cell and user throughputs over using fixed beamforming without code reuse.

CONCLUSIONS

We have evaluated a wide range of IA deployment scenarios based on practical antenna configurations that can significantly enhance the baseline performance of UMTS in both uplink and downlink. Extensive simulation results were presented that verified the benefits of intelligent antennas to dedicated, connectionless, and

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4 This assumes that the angle spread seen at the base station antenna array is small.
Figure 17. Statistics of user service throughput; full buffer traffic; Rake receiver.

HSPSD channels. Universal beamforming and multibeam scheduling paired with RF optimization techniques in the field can significantly improve system capacity. The challenging problem of implementing a practical IA solution suitable for macrocellular environments was addressed by combining practical choices on the antenna configuration and innovative design on both physical and MAC layer algorithms.

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SHIRISH NAGARAJ received Ph.D. and M.S. degrees from the University of Notre Dame, Indiana, in October 2000 and May 1997, respectively, and a B. Tech. degree in electrical engineering from the Indian Institute of Technology, Bombay, in May 1995, all in electrical engineering. He was a research intern at Lucent Technologies-Bell Laboratories, May–December 1998. Since October 2000 he has been with Lucent Technologies-Bell Laboratories, Whippany, New Jersey, as a member of technical staff in the Wireless Signal Processing group. He is a recipient of the Best Researcher Award from the University of Notre Dame in May 2001. His research interests include statistical and adaptive signal processing, multi-user detection, wireless communications, and adaptive antennas. The current focus of his work is design of algorithms and analysis of system-level performance for voice and packet data cellular networks with multiple antennas.

ANIL M. RAO received a B.S. degree in applied math in 1995 from the University of Alaska, Fairbanks, and M.S. and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana-Champaign in 1997 and 2001, respectively. During the summers of 1995, 1996, and 1998 he was employed at NASA’s Jet Propulsion Laboratory, Pasadena, California, and during summer 2000 was employed at TRW, Redondo Beach, California. He was a National Science Foundation graduate research fellow, 1997–2000. He is currently employed by Lucent Technologies in Whippany, New Jersey. His research interests are in array processing, signal detection and estimation, and wireless communications.

Robert A. Soni is a technical manager at Lucent Technologies, Bell Laboratories within the Open Innovation Laboratory of the Mobility Sector. His current projects and interests include study and performance analysis of multiple antenna systems for wireless applications, transmit diversity for CDMA systems, adaptive antennas, network system performance modeling, and signal processing for wireless applications. He has co-authored numerous journal and conference papers, and holds four patents in the area of wireless communication. He received a B.S.E.E. (summa cum laude) degree from the University of Cincinnati, Ohio, in 1992, and M.S.E.E. and Ph.D. degrees from the University of Illinois at Urbana-Champaign in 1995 and 1999, respectively.

YIFEI YUAN received B. Eng. and M. Eng. degrees from Tsinghua University of China in 1993 and 1996, and a Ph.D. from Carnegie Mellon University in 2000. He has been at Lucent since 2000 as a member of technical staff working on signal processing, intelligent antennas, and chip design for UMTS networks. His research interests are multiple antenna systems, equalization, error correction coding, and so on.