The IST METRA Project

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ABSTRACT

This article summarizes the main achievements of the Multi-Element Transmit and Receive Antennas (METRA) Project, an IST research and technological development project carried out between January 2000 and June 2001 by Universitat Politècnica de Catalunya, the Center for Personkommunikation of Aalborg University, Nokia Networks, Nokia Mobile Phones, and Vodafone Group Research and Development. The main objective of METRA was the performance evaluation of multi-antenna terminals in combination with adaptive antennas at the base station in UMTS communication systems.[1] A MIMO channel sounder was developed that provided realistic multi-antenna channel measurements. Using these measured data, stochastic channel models were developed and properly validated. These models were also evaluated in order to estimate their corresponding channel capacity. Different MIMO configurations and processing schemes were developed for both the FDD and TDD modes of UTRA, and their link performance was assessed. Performance evaluation was completed by system simulations that illustrated the benefits of MIMO configurations to the network operator. Implementation cost vs. performance improvement was also covered by the project, including the base station and terminal manufacturer and network operator viewpoints. Finally, significant standards contributions were generated by the project and presented to the pertinent 3GPP working groups.

INTRODUCTION

Recent research in antenna array processing has shown that space-time architectures combining the use of multiple antenna elements at both the transmitter and receiver ends (i.e., deploying antenna arrays at both mobile and base station equipment) has very significant capacity and/or range expansion potential. In particular, it was shown that capacity could be increased as much as linearly with the number of antenna elements with respect to the classic Shannon equation [1].

For Universal Mobile Telecommunications System (UMTS) terrestrial radio access (UTRA) handy mobile terminals devoted to voice and low-data-rate services, the requirement for multi-antenna architectures remains unclear. It is, however, manifestly accepted that adaptive base station antennas combined with transmit and receive diversity yield a more cost-efficient solution when higher-data-rate services are to be provided.

The incorporation of space-time processing capabilities in mobile terminals has not generally been taken into consideration, the reason being the potential cost and size of the mobile terminal. Nevertheless, employment of multiple antennas at user equipment is potentially beneficial when providing high-bit-rate (typically multimedia) services. This is due to the fact that mobile terminals providing these kinds of services are compelled to be bigger than today's mobile phones because of the more sophisticated man–machine-interface (MMI) (display, camera, keyboard, etc.).

High-data-rate terminals are likely to incorporate some type of screen to display information. The size, price, and power consumption of the radio part of the terminal is therefore less important than for terminals providing speech services only. A multiport antenna configuration built into the terminal equipment can be made very compact and still provide partially decorrelated signal branches.

MAIN PROJECT ACHIEVEMENTS

This section provides a general description of some of the main achievements of the project from a technical perspective.

MIMO CHANNEL CHARACTERIZATION

Although the characterization of wireless channels started some decades ago, and has been the subject of intense research activities since then,

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[1] Full details of the METRA project including public deliverables, published papers and presentations are available at the METRA Web page: www.ist-metra.org.

it still attracts much interest. One of the main reasons for this continuing interest is the fact that, until some years ago, most modeling activities focused on the time-domain aspects. This led to a large set of models that can be classified according to the outdoor vs. indoor dichotomy. Usually, in outdoor scenarios, the base station (BS) is assumed to be placed much higher than the mobile station (MS), such that the scatterers which account for the diffuse transmission of the signals mostly lie close to the MS. On the contrary, the surrounding environment is usually much more similar for MS and BS in indoor scenarios, thus introducing some symmetry in the phenomena. This dichotomy led to the development of two sets of models, the first accounting for outdoor mobile scenarios, the second for indoor portable ones. The models proposed by [2, 3] are among the most widely accepted for outdoor environments. They account for the time dispersion and time variation of mobile channels. On the other hand, the model proposed in [4] appropriately describes indoor phenomena.

These time-domain models were applied successfully until quite recently, when the growing demand for ubiquitous high-speed connections pushed researchers to investigate new means of increasing the capacity of wireless channels. As part of these efforts, the use of so-called *smart antennas* for antenna/space diversity, beamforming, and even space-division multiple access (SDMA) have been regarded as powerful improvements [5]. However, the classical models of radio channels were of no immediate help, since they are nondirectional, and thus do not appropriately model the propagation phenomena in the space domain. There have been many proposals of models solving this lack. Some proposed an upgraded version of time-domain models. Others suggested new models, based on either a geometric description of the scattering process used to compute power delay spectrum (PDS) and power azimuth spectrum according to propagation laws, or empirical models fitting measurement results. References [5, 6] present comprehensive surveys of these efforts.

The target of the Multi-Element Transmit and Receive Antennas (METRA) project was to study the feasibility of introducing multi-element adaptive antennas into the user equipment and the BS for third-generation mobile communication systems. Thus, one main objective was to gain a better understanding of the characteristics of the multiple-input multiple-output (MIMO) radio channels in a wide variety of environments. A stochastic model has been proposed and its implementation in COSSAP®, a widely used simulation tool, made public.

A major characteristic of the stochastic model is that, contrary to other directional models, it does not rely on a geometrical description of the environment under study. The spatial correlation information collapses into a pair of matrices, one for each connection termination. The elements of each of these matrices are the correlation coefficients of the antennas at the corresponding termination. The two matrices are combined by a Kronecker product into the spatial correlation matrix of the channel. Generating the spatially correlated taps of a MIMO tapped delay line model is then achieved by means of a coloring matrix, which is obtained from a Cholesky decomposition of the Kronecker product outcome. Guidelines for choosing the element values of these two correlation matrices according to the environment under consideration, as well as the PDS and Doppler spectrum characterizing its time-domain behavior, have also been given.

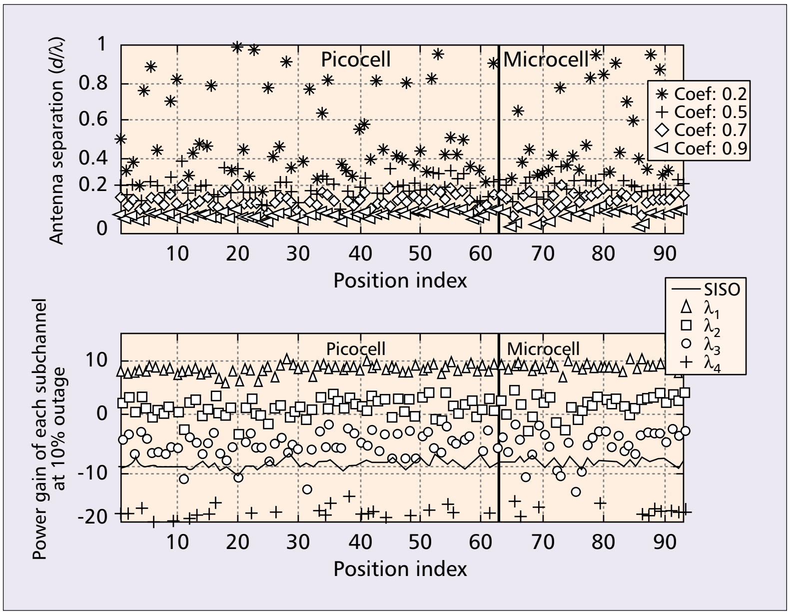

Figure 1. *Eigenanalysis characterization of the 99 investigated positions.*

A total of 99 positions in six different pico- and microcell environments have been considered. Their measurement results have been presented through the eigenanalysis of the correlation matrix of the measured channel. In rich scattering environments, the MIMO channel is spatially decorrelated. The eigenanalysis of its correlation matrix reveals the means to excite the channel in a way that enables an optimal set of parallel orthogonal subchannels to be identified. The power gains of these subchannels are the eigenvalues, provided that the eigenvectors are applied as weights at the connection terminations.

Conversely, for a given scattering environment, the eigenanalysis helps to estimate the antenna spacing required to achieve a given decorrelation, and therefore enjoy the capacity increase delivered by the orthogonal subchannels. The top graph of Fig. 1 shows this spacing at the UE for a (4, 4) setup. In most investigated cases, a small spacing (half a wavelength) is enough to significantly decorrelate antenna elements. Moreover, the results of the bottom graph give an estimate of the eigenvalues (denoted λ_1–λ_4). They have been compared to those derived from the analysis of the synthesized channel generated by the COSSAP implementation of the proposed stochastic model, as a means to validate it through matching of the eigenanalysis results. A detailed description of the measurement campaign and the associated stochastic model are to be found in METRA Deliverable 2, "MIMO Channel Characterization" available at the project Web page.

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Transmit Techniques in the FDD Mode of UTRA: Comparison of Layered MIMO Techniques and a Punctured Scheme

Layered schemes like the well-known Lucent BLAST concept [7] are MIMO techniques in which multiple parallel data streams are transmitted simultaneously, each from its own transmit antenna. A particularly simple version of BLAST named Vertical BLAST was proposed in which the receiver, equipped with multiple antennas, is able to recover the complete data sequence using a successive interference rejection and cancellation approach [8]. Two different versions of a layered MIMO scheme, which are similar to BLAST, have been tested. These layered schemes are tested against a so-called punctured scheme that achieves the double data rate by heavily puncturing the channel code (convolutional code). In practice, this means that rate 1/3 code is punctured to rate 2/3. A (2, 2) MIMO channel is utilized by applying space-time transmit diversity (STTD), which applies the well-known Alamouti space-time block code for two transmit antennas, and a dual-antenna Rake for receive diversity. Additional information is presented in METRA Deliverable D4, "Performance Evaluation," available at the project Web page.

Layered Scheme 1 — Figure 2a shows the general structure of the first layered (2, 2) MIMO scheme under consideration. A frame of data is split into two streams that are separately convolutionally encoded and transmitted from two antennas. The antennas transmit different pilot sequences so that the receiver is able to estimate both channels.

The receiver first selects the transmit antenna that is received with the highest power. This selection is optimal in single-path channels in the sense that post-detection mean square error (MSE) is minimized. In the tested pedestrian channel the selection is near optimal while it avoids complex matrix inversion that otherwise would be required to determine the best transmit (TX) antenna. The selected TX antenna signal is detected using a linear minimum MSE (LMMSE) receiver applying direct matrix inversion (DMI) to compute the receiver weights. The dual-antenna LMMSE receiver is able to suppress one interfering signal (from the other TX antenna) very effectively. Unfortunately, this results in loss of receive diversity (roughly from order 2 to order 1).

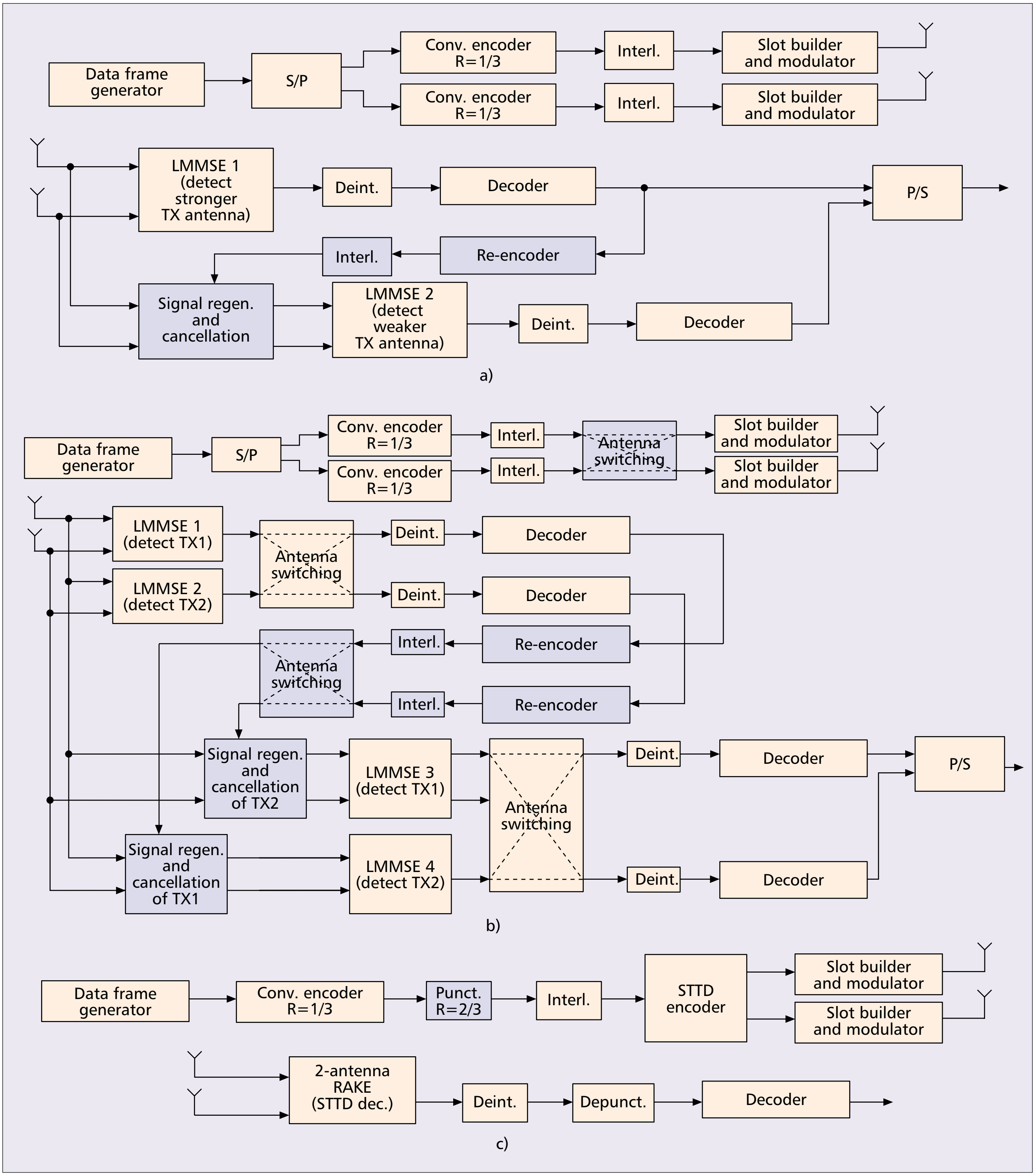
The detected signal is reencoded, reinterleaved, reconstructed, and cancelled from the received signal. The other TX antenna signal is then detected as usual, using another dual-antenna LMMSE receiver. The outputs of the two LMMSE receivers are combined to produce the detected data frame.

Layered Scheme 2 — Figure 2b shows the structure of the second layered scheme under analysis. Since layered scheme 1 transmits each channel encoded code word from a separate antenna, the system does not offer any transmit diversity. Moreover, the reception reliability of the code words is different due to the use of uncorrelated transmit antennas (this was taken into account by first selecting the better TX antenna at the receiver). In layered scheme 2, transmit diversity is achieved by switching the code word symbols between the two transmit antennas at the symbol rate. The channels perceived by the two code words are also the same. The antenna switching procedure causes some changes in the receiver. Two dual-antenna LMMSE receivers detect each of the transmit antennas, and the two code words are reconstructed by removing the effect of antenna switching. After decoding, both streams are reencoded, reinterleaved, reconstructed, and cancelled from the received signal. After cancellation the signals are once again detected by two dual-antenna LMMSE receivers. The output of these receivers is then parallel-to-serial converted to form the original data frame.

Punctured Scheme — Figure 2c illustrates the structure of the transmitter and receiver for the punctured scheme, which also achieves twice the data rate of conventional transmission techniques. The punctured scheme offers full transmit diversity by using STTD and full receive diversity by using dual-antenna Rake. It is important to note that the complexity of this technique is only a fraction of the complexity of the layered scheme. Moreover, the performance of the punctured scheme would further improve if a dual-antenna LMMSE receiver were used. The punctured scheme closely follows the current UTRA FDD downlink specifications.

Figure 3a shows the performance of the layered schemes and the punctured scheme in the two-path pedestrian channel (3 km/h) in terms of frame error rate (FER) vs. signal-to-interference ratio. All these techniques result in twice the data rate of conventional single-antenna transmission, also shown in Figure 3a. Power control has not been modeled in these simulations.

The punctured scheme seems to offer twice the data rate with approximately the same TX power than the best layered scheme, but with significantly lower complexity. The effect of transmit antenna hopping used in layered scheme 2 is clearly visible. Without hopping, the lack of diversity degrades the performance of layered scheme 1 because the pedestrian channel offers almost no multipath diversity. Its performance is, however, similar to single-antenna TX which offers only half of the data rate. This is actually an expected result since the FER performance is dominated by the block errors occurring in the detection of the strong TX antenna (which is first selected in the receiver). The reason for this is that, when detecting the stronger TX antenna, the dual-antenna LMMSE suppresses the other TX antenna signal but, at the same time, suffers a loss in the receive diversity order. Therefore, the stronger antenna is in effect detected in a (1, 1) MIMO channel, and the total FER should be close to conventional 1-TX 1-RX system. The punctured scheme closely follows the current UTRA frequency-division duplex (FDD) downlink specifications the only differences being the obvious changes in puncturing or rate matching, and the use of a dual-antenna receiver which could be indirectly



■ **Figure 2.** *a) Transmitter and receiver for layered scheme 1; b) transmitter and receiver for layered scheme 2; and c) transmitter and receiver for the punctured scheme.*

included in the specifications in the form of tightened performance requirements for high data rate terminals.

Figure 3b illustrates the performance in the five-path vehicular channel (50 km/h). Since the multipath diversity order due to the channel is high, the TX antenna switching is not providing a significant gain. Layered scheme 2 is still better than the first scheme, however, because its LMMSE reception is much more complex. Still, the punctured scheme can achieve the same performance as the layered schemes at lower FER levels. This is probably due to the LMMSE capability to suppress multiple access interference (MAI). If dual-antenna LMMSE was used instead of dual-antenna RAKE, the punctured scheme is expected to outperform the other techniques.

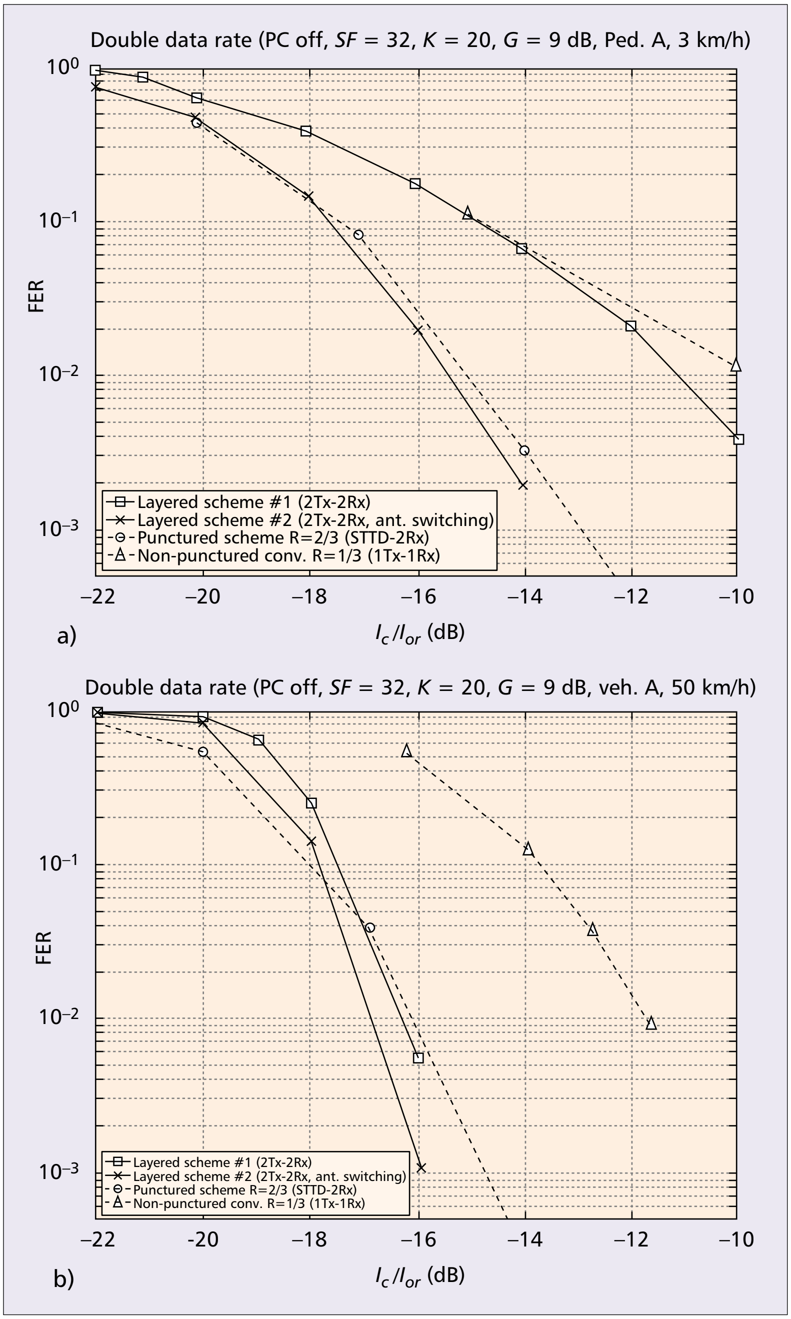


Figure 3. *a) Layered and punctured schemes in pedestrian channel; b) layered and punctured schemes in vehicular channel.*

A conclusion is that in lower-order MIMO channels such as (2, 2) MIMO, puncturing and TX and RX diversity is superior to layered BLAST-like MIMO techniques in terms of complexity and performance. The proposed punctured scheme has been included in a Third Generation Partnership Project (3GPP) technical report [9] as an option for layered schemes in low-order MIMO channels. It should be noted that puncturing could not offer extremely high data rates since the channel code rate sets the limit. However, this study has concentrated on dual-antenna mobile receivers to limit the complexity. This also limits the number of parallel data streams in layered techniques to a maximum of two.

Transmit Techniques in the TDD Mode of UTRA

This section describes the multi-element transmit techniques that were considered for the time-division duplex (TDD) mode of UTRA. The techniques are classified into two groups: standard-friendly and standard-nonfriendly. The techniques currently considered by the standard or that could be introduced without major modifications of the signal format are analyzed in the first group. The second group includes techniques that cannot be implemented according to current UTRA specifications but might easily be introduced in future versions. Detailed simulation results of these techniques can be found in METRA deliverable D4, "Performance Evaluation," available at the project Web page.

Standard-Friendly Techniques — Two different transmit standard-friendly techniques are considered: a narrowband beamforming scheme and a space-time block coding architecture.

Beamforming. For the closed loop downlink diversity scheme the current 3GPP specifications propose a narrowband beamforming approach, where a different spatial filter is used for each of the intra-cell users. Since each UE sees a different equivalent channel, one midamble per user has to be used. Note that in the TDD mode of UTRA, unlike in FDD mode, closed loop operation is based on the reciprocity between uplink and downlink channels. This is a valid assumption as long as the delay between channels is small compared to the coherence time, as is usually the case in indoor environments.

Alamouti Space-Time Block Code. The TDD mode of UTRA does not consider space-time codes for the dedicated physical channels (DPCHs) and only allows for the potential introduction of the Alamouti code [10] in the primary common control physical channel (P-CCPCH) and, more recently, in the paging indicator channel (PICH). In our simulations, though, we considered a combination of the space-time Alamouti code for the DPCH channel plus beamforming architecture. The four available transmit antennas were grouped into two groups of two, and a different beamforming was applied to each group, as shown in Fig. 4a.

Standard-Nonfriendly Techniques — As standard-nonfriendly techniques a layered architecture (vertical BLAST) and a four-antenna space-time block code (STBC) were evaluated.

Layered Architecture (BLAST). This corresponds to the case of using no beamforming, as illustrated by the BLAST architecture in Fig. 4b, and the transmitter does not require any channel state information. The data are demultiplexed into four different substreams, each transmitted from a different antenna. Since this scheme inherently increases the data rate by a factor of 4, we first apply a convolutional code with rate 1/4 to fix the overall spectral efficiency of all architectures under consideration. At the receiver, and after multiplexing the detected received

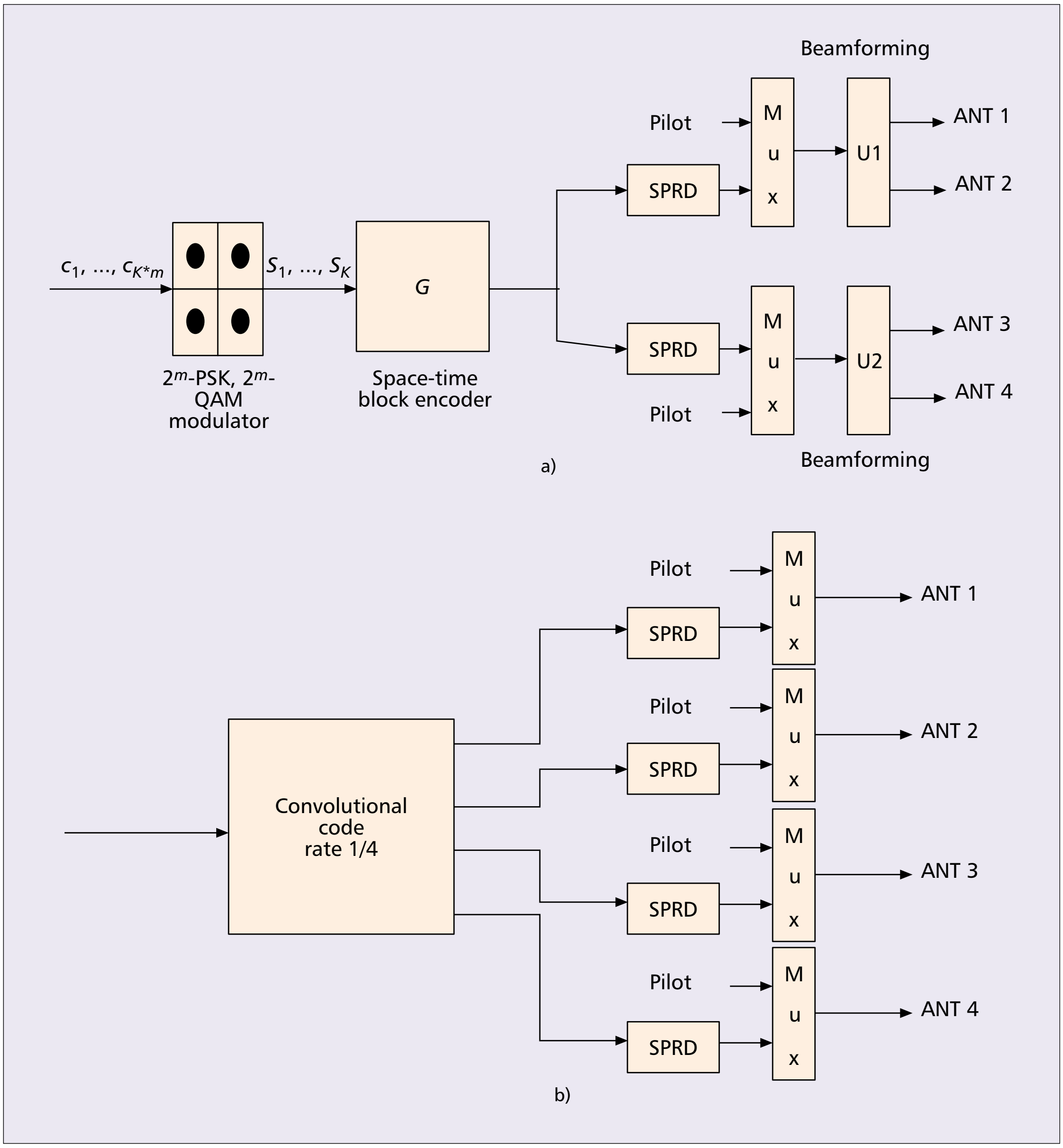


Figure 4. *4a) Combined Alamouti code and beamforming; b) layered architecture (V-BLAST).*

The basic difference between receivers in the two modes is the following: in the uplink the base station receiver knows everything about the intra-cell users, whereas in the downlink the mobile unit receiver does not usually have access to that information.

data symbols, a Viterbi detector is used to decode the sequence and recover the original transmitted data.

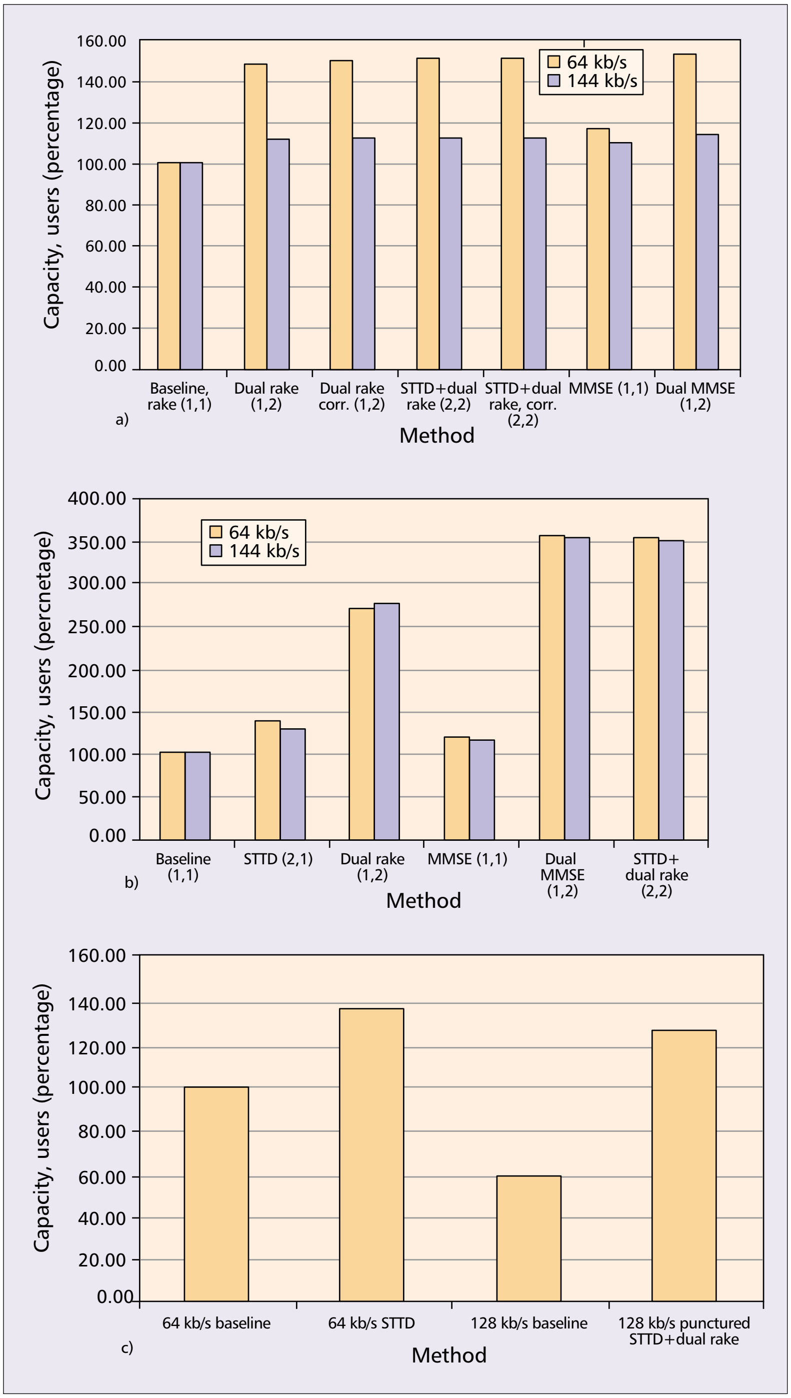
Four-Antenna STBC. It is well known that full-rate STBCs for complex constellations and more than two transmit antennas do not exist. In general, these space-time codes double the required bandwidth (code rate 1/2), but few sporadic codes can be obtained that have a code rate closer to 1. For the case of four transmit antennas the following space-time block code has been considered, which provides a rate 3/4:

$$C = \begin{pmatrix} x_1 & x_2 & \frac{x_3}{\sqrt{2}} & \frac{x_3}{\sqrt{2}} \\ -x_2^* & x_1^* & \frac{x_3}{\sqrt{2}} & -\frac{x_3}{\sqrt{2}} \\ \frac{x_3^*}{\sqrt{2}} & \frac{x_3^*}{\sqrt{2}} & \frac{-x_1 - x_1^* + x_2 - x_2^*}{2} & \frac{+x_1 - x_1^* - x_2 - x_2^*}{2} \\ \frac{x_3^*}{\sqrt{2}} & -\frac{x_3^*}{\sqrt{2}} & \frac{+x_1 - x_1^* + x_2 + x_2^*}{2} & \frac{+x_1 + x_1^* + x_2 - x_2^*}{2} \end{pmatrix}$$

Receive Techniques in the TDD Mode of UTRA

Two different types of receiver architectures have been considered: uplink- and downlink-oriented. The basic difference between receivers in the two modes is the following: in the uplink the BS receiver knows everything about the intracell users (e.g., spreading and scrambling codes, training sequences), whereas in the downlink the mobile unit receiver does not usually have access to that information. One could therefore classify the techniques into single- and multi-user receivers instead, although it is clear that these two viewpoints translate differently in the uplink and downlink scenarios. In any case, and merely for comparison purposes, multi-user approaches have also been simulated at the mobile station.

Uplink-Oriented Techniques — In the uplink, the receiver BS has knowledge of the spreading codes and training sequences of all intracell users present in the scenario. Thus, multi-user techniques seem most appropriate for the recep-



■ **Figure 5.** *a) System performance of downlink receive diversity; b) system performance of combined downlink transmit and receive diversity; and c) double data by punctured STTD (downlink only).*

tion of uplink communications. Two types of linear multi-user receivers were analyzed.

Multi-User Denoised Matched Filter (DMF). According to this approach, the receiver estimates the noise plus intercell interference covariance matrix and applies a matched filter after having whitened the received data. This approach is equivalent to a single user matched filter except for the fact that an intercell interference covariance matrix is applied.

Multi-User LMMSE Receiver. In this case the receiver also estimates the noise plus intercell interference, but instead of using it to whiten the received snapshots, it is included as a noise term in the multi-user LMMSE receiver. It requires a multi-user channel estimation procedure.

Downlink-Oriented Techniques — These techniques are limited by the fact that the UE only possesses knowledge about the spreading code and training sequence corresponding to its own channels. Thus, they could also be referred to as *single-user receive techniques*.

Single-User DMF. In this case, the receiver estimates the global noise-plus-interference correlation matrix, including both intra- and intercell interference components, and uses it to whiten the received signal. After that, a conventional matched filter is applied.

Single-User LMMSE. Here again the global interference-plus-noise correlation matrix is calculated, although the result is used to construct an LMMSE equalizer. Note that the basic difference between this approach and single-user DMF is the fact that the received signal is equalized before detection. We will see that this leads to very low performance gains with respect to that receiver, especially when considering low-dispersive indoor scenarios.

Detection of Space-Time Block Codes. The STBCs are detected with a multi-user LMMSE receiver, where the signal arriving from each antenna is treated as a separate user. The output of the LMMSE detector is recombined according to the code characteristics, and detection is performed on the corresponding soft outputs.

Reception of BLAST Streams. The reception of BLAST streams is made using the multi-user LMMSE receiver, where the signal transmitted from each antenna is treated as a different user. That is, the receiver estimates the noise-plus-interference covariance matrix (containing both intra- and intercell interference components) and uses it as the *noise term* in the LMMSE receiver, where each detected user corresponds to a communication through a different antenna.

System Simulation Results

Transmit and Receive Diversity — This section presents the results for standard-friendly transmit and receive diversity techniques for the FDD mode of UTRA. The expression *corr* indicates that the link-level simulation was carried out with correlated antennas. The results are expressed as percentage increase of capacity in number of users supported by the system for the different schemes under consideration.

In Fig. 5a simulations were done with both the uplink and downlink enabled, so calls have failed on both links. It shows clearly that the addition of a second antenna at the UE for receive diversity provides substantial performance gains for 64 kb/s service. For 144 kb/s service the downlink power allocation is such that the downlink and uplink are more closely balanced than for the 64 kb/s service. Therefore, there is less room for improvement on the downlink before the uplink becomes the limiting link. These results show that the capacity increase is limited for symmetrical services when a diversity (or other advanced technique) is applied to one link only. The other will become the limiting factor, and unless a diversity (or other) method is applied on the other link, the large gains for a single link (Fig. 5b) cannot be obtained.

Figure 5b considers the downlink in isolation. STTD gives a user capacity increase of 37 percent; it is likely that closed loop methods (in suitable environments) will provide similar gains. Again, a second antenna on the UE gives large gains, such that for 144 kb/s service the dual LMMSE receiver could lead to some cells being code limited on the downlink. It is interesting to note that the performance of the dual LMMSE is marginally better than the simple multi-antenna system of STTD plus dual Rake receiver. The gains presented here are derived from the improvement in transmitted E_b/N_0 that was observed in the link-level simulations.

STTD with Puncturing — The aim of this technique is to double the data rate by puncturing the channel code from rate 1/3 to 2/3, while applying STTD.

The initial link-level evaluation sought to compare this method with a (2,2) BLAST system. Those results showed that (2,2) BLAST provided double the data rate for the same transmitted E_b/N_0 (Fig. 5a and b). Consequently this would lead to the same number of users as the 64 kb/s baseline but at 128 kb/s. Figure 5c, however, shows that punctured STTD plus a dual rake antenna at the UE (therefore also a (2, 2) system) provides twice the data rate while actually increasing the number of users.

Main Project Results

The system simulation results described above show that significant gains are possible from standard-friendly MIMO techniques. Important results are:

- Compatibility of all methods in an earlier section with the current 3GPP UTRA (FDD mode) standard, enabling the implementation of simple (2, 2) MIMO
- Enhancement in data rate and increase in users from a simple (2, 2) MIMO system of STTD with punctured code transmission and dual antenna Rake reception
- Performance of the dual antenna LMMSE at the UE

The results show that there are significant gains available for each link in isolation (i.e., would be available for asymmetrical services), but applying a diversity method on one link only limits the capacity increase for symmetrical services. Further work is required to assess UL transmit diversity techniques at system level, and standard-nonfriendly methods (e.g., BLAST, space-time Turbo codes) need to be analyzed.

Table 1 gives a rough summary of the complexity increase when introducing multiple antennas at the base and user equipment. Software complexity is related to the operations (multiplications and additions) per second the algorithm requires, while hardware complexity and cost are related to the number of additional antennas and related electronics vs. the conventional BS and mobile unit implementation. When estimating the impact of software it has been assumed that higher-layer software, such as the user interface and telecom software to the network controller, dominates the complexity. It is clear that the table gives only very coarse guidelines; for example, the software complexity numbers represent only practical, suboptimal algorithms. Cost impact is mainly related to harware complexity. The issue is further discussed in METRA Deliverable D5, "Cost versus Benefit Trade-offs of Multi-Element Transmit and Receive" available at the project Web Page.

	Approximate peak data rate (spectral efficiency)					
	2 Mb/s (reference)		4 Mb/s (2 × 2 MIMO)		8 Mb/s (4 × 4 MIMO)	
	HW	SW	HW	SW	HW	SW
UE	100%	100%	150%	120%	300%	140%
BTS	100%	100%	120%	110%	150%	120%
Network	100%	100%	120%	120%	150%	150%
	Estimate of relative complexity and cost. HW: hardware; SW: software					

Table 1. *Complexity associated with the utilization of multiple antennas.*

Conclusions

The main objective of the METRA project was to analyze the feasibility and evaluate the performance of introducing multi-element adaptive antennas into mobile terminals in combination with adaptive base station antenna arrays, including transmit diversity, for third-generation mobile communication systems with emphasis on UMTS.

The results of the project are described in detail in the project deliverables, available from the project Website. Some of the significant achievements are:

- The development of a publicly available MIMO channel model, which has been benchmarked against MIMO channel measurements. This model is currently under consideration for work within the 3GPP Technical Specification Group RAN WG1.
- Extensive link-level analysis of a range of diversity techniques including, but not limited to, 3GPP transmit diversity, BLAST, and STBC.
- FDD system-level simulations investigating the performance enhancement offered by MIMO techniques.

The METRA project has made substantial strides in understanding the potential of MIMO channels and techniques to exploit them. However, there has been an explosion of interest in this field since METRA started, and new methods are emerging continually. How multi-element arrays will interact with techniques such as advanced modulation and coding schemes, and advanced packet scheduling, which are expected to become essential in evolutions of 3G and beyond also requires investigation. All the partners are involved in the I-METRA project (http://www.ist-imetra.org) which seeks to enhance and extend the work of METRA.

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BIOGRAPHIES

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