WIRELESS WORLD
RESEARCH FORUM

On the Performance of Multiuser MIMO Systems in Beyond 3G: Beamforming, Feedback and Scheduling

James S. Kim*, Student Member, IEEE,* Antonio Forenza*, Student Member, IEEE,*
Marios Kountouris*, Student Member, IEEE,* Hojin Kim*, Member, IEEE,*
Chang Soon Park*, Student Member, IEEE,* Ashish Pandharipande*, Member, IEEE,*
and Kwang Bok Lee*, Senior Member, IEEE*

***Abstract*—In WCDMA/HSDPA of 3GPP, several multiple-input multiple-output (MIMO) techniques have been proposed and in progress of performance evaluation for comparison. Most MIMO candidates in HSDPA have been generally designed based on a point-to-point communication, which means that a single-user capacity is of major concern. However, multiple users and user scheduling need to be considered for wireless packet transmission in beyond 3G, so as to maximize system throughput. In this paper we propose the multiuser MIMO scheme with the effective user scheduling technique in both space and time domains accompanying three main features, which are the spatial-beamforming, uplink feedback signaling, and user scheduling. We also investigate the impact of feedback signaling. Simulation results show that the proposed scheme has higher user diversity gain than other MIMO candidates in terms of ergodic capacity.**

***Index Terms*— Multiuser MIMO, Beam-forming, Feedback and Scheduling**

INTRODUCTION

In the third generation wireless mobile communications (e.g., wideband code division multiple access (WCDMA)), high-rate data transmission needs to be supported for wireless multimedia services. High speed downlink packet access (HSDPA) is a solution to achieve a bit rate of 10Mbps, which includes various technologies such as adaptive modulation and coding (AMC), hybrid automatic repeat request (HARQ), fast cell selection (FCS), and multiple-input multiple-output (MIMO) antenna processing [1]. Recently, MIMO techniques have been an active area as a work item, which increases data rate as well as spectral efficiency [2]–[7]. In practical channel environments, multiuser signaling is of significant concern for system design [8]–[11]. A scheduling algorithm must be considered for capacity improvement in a multiuser MIMO while a single-user MIMO is designed to improve a point-to-point link capacity [12]–[13]. In this paper, we propose a novel multiuser MIMO scheme which exploits user diversity for scheduling users and adapts the transmit beamforming based on the feedback information. We also investigate the scheduling schemes when combined together with advanced receiver. Furthermore, we compare the system performance of our proposed multiuser MIMO scheme with other candidates.

Multiplexing MIMO Schemes

Per-Antenna Rate Control (PARC)

Lucent initially proposed their multiple antenna solution, which is called the per-antenna rate control (PARC), in 3GPP MIMO technical report (TR) [14]. The transmitter structure of PARC is shown in Fig. 1, in which separately encoded data streams are transmitted from each antenna with equal power but possibly with different data rates while spreading code is reused through all streams. The data rates for each antenna are controlled by adaptively allocating transmit resources such as modulation order, code rate, and number of spreading codes. The post-decoding signal-to-interference-plus-noise ratio (SINR) of each transmit antenna is estimated at the receiver and then fed back to the transmitter, which is used to determine the data rate on each antenna. The vector signaling with more feedback overhead over the scalar signaling in conventional systems is required for link adaptation [14].

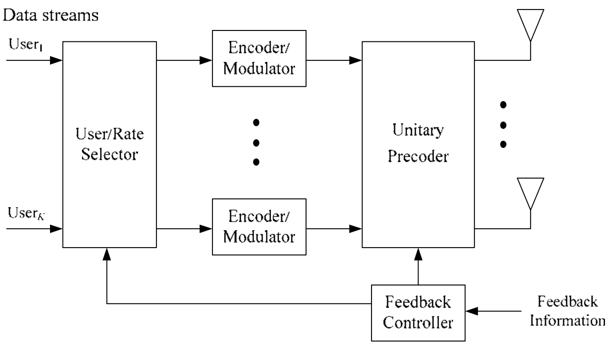

Figure 1. Schematic of PU^{2}RC transmitter

Assume that M_t and M_r are the number of transmit and receive antennas, respectively, MIMO channel is a block fading model and represented by the M_r x M_t matrix H_k, n_k is a M_r x 1 noise (AWGN) vector, and E_s is the total transmit energy, where both H_k's and n_k's have i.i.d. complex Gaussian distribution with zero mean and the variance of one and the variance of N_0, respectively, and k is the index of each user. Then, the M_r x 1 received signal vector for the kth user in multiuser MIMO systems is expressed as

$$\mathbf{y}_k = \sqrt{\frac{E_S}{M_t}}\mathbf{H}_k \mathbf{x}_{S,k} + \mathbf{n}_k$$

where k = 1, …, K, and $\mathbf{x}_{S,k}$ is the M_t x 1 transmitted symbol vector for the kth user with the power constraint such that $\mathbf{E}[\mathbf{x}_{S,k}\mathbf{x}^H_{S,k}] = \mathbf{I}_{Mt}$. In contrast to multiuser schemes, only one user is served at a time. To show the received SINR, i.e., the post-decoding SINR, and the capacity performance of PARC, when minimum mean-squared error (MMSE) filtering and SIC are applied to receivers, i.e., SIC receivers [6],

The capacity is then

$$C_k = \sum_{m=1}^{M_t} c_f(\gamma_{S,k,m})$$

where $c_f(\gamma) = \log_2(1 + \gamma)$ and $\gamma_{S,k,m}$ is the received SINR of the mth stream.

Selective PARC (S-PARC)

The selective PARC (S-PARC) has been proposed by Ericsson, which is conceptually based on PARC scheme in the previous subsection [15]. In S-PARC, selection diversity is combined together with PARC by controlling transmit antenna configurations with adaptive resource allocations. Recent results have shown that PARC achieves the full open-loop capacity of the flat fading MIMO channel [14]. However, there is a significant gap between the open-loop capacity and the closed-loop capacity, when signal-to-noise ratio (SNR) is low and/or the number of receive antennas is less than the number of transmit antennas. An approach to achieve the near-capacity of the closed-loop MIMO is S-PARC, which compensates for the capacity loss by the gain of antenna selection.

Multiuser Precoding MIMO Scheme

In this section, we describe the system model and investigate our method of transmit beamforming using the unitary basis matrix for multiuser MIMO transmission. The proposed scheme has two main benefits, precoding gain and downlink multiuser diversity. The precoding gain is achieved through transmit unitary basis transformation, which results in capacity and error rate improvement. Multiuser diversity in space-time domain maximizes the sum capacity of vector channels to all users and may provide significant capacity gain compared to multiplexing-based systems when the number of transmit antennas is larger than the number of receive antennas. Our scheme employs signaling to feed back the channel information such as received SINR, subspace structure of channel matrix, and receiver structure, which are important to determine the performance of the link throughput [16].

Per-User Unitary Rate Control (PU²RC)

We propose the multiuser MIMO scheme using the unitary basis matrix, which is called the per-user unitary rate control (PU²RC) [17], [18]. The proposed system model is shown in Fig. 1. Applying the same assumptions used in PARC, the received signal vector is given by

$$\mathbf{y}_k = \sqrt{\frac{E_S}{L}}\mathbf{H}_k\mathbf{x}_\mathrm{M} + \mathbf{n}_k$$
$$= \sqrt{\frac{E_S}{L}}\mathbf{H}_k\mathbf{T}\mathbf{s} + \mathbf{n}_k$$

where $L \le M_t$ is the total number of transmit streams, $\mathbf{x}_\mathrm{M} = \mathbf{Ts}$, $\mathbf{T} = [\mathbf{t}_1, \ldots, \mathbf{t}_L]$ is the beamforming matrix, and $\mathbf{s} = [s_1, \ldots, s_L]^T$ is the transmit signal vector with the power constraint such that $\mathbf{E}[\mathbf{ss}^H] = \mathbf{I}_L$. Since PU²RC is a multiuser MIMO scheme, each s_i can be allocated to a different user independently. We let the beamforming matrix $\mathbf{T}$ be a unitary matrix, i.e., $\mathbf{T}^H\mathbf{T} = \mathbf{I}_L$, so as to improve the capacity obtained by the matched filter beamforming (hereafter denoted by unitary matched filter beamforming (UMF-BF)). UMF-BF is simpler to implement than other transmit precoding methods such as dirty-paper coding (DPC) and MMSE beamforming, and it yields significant capacity gain when combined with space-time user diversity. It follows from [4] and [18] that the sum rate of both UMF-BF and DPC scales like M_t log logKM_r when K is large. To utilize user diversity in the space and time domains, $\mathbf{T}$ is obtained by

$$\mathbf{t}_l = \arg\max_{\mathbf{v}_{k,m}} c_f\left(\rho_k(\mathbf{v}_{k,m})\right),\ l = 1,\ldots,L$$

where $\mathbf{v}_{k,m}$ is the quantized version of the mth eigenvector of $(\mathbf{H}^H_k\mathbf{H}_k)$ by using a subspace packing such as Grassmannian line packing [16], and $\rho_k(\mathbf{v}_{k,m})$ is the received SINR function of user index k and beam vector $\mathbf{v}_{k,m}$ [17].

Feedback Signaling Scheme

The closed-loop MIMO obtains channel information at the transmitter through feedback channel. In this subsection, we describe the characteristics of feedback information in PU²RC, and design feedback signaling protocols. In PU²RC, two types of channel information are fed back to the transmitter: the beamforming vectors and the corresponding channel qualities. More specifically, the beamforming vectors and the channel qualities are the quantized eigenvectors of each user, i.e., $\{\mathbf{v}_{k,m}\}_m$, and the received SINRs, i.e., $\{\rho_k(\mathbf{v}_{k,m})\}_m$, respectively. We consider quantized vectors from the set predefined by a subspace packing, where the beam selection is preferable to the eigen-decomposition which is practically difficult to implement. In particular, the set of selected vectors corresponds to the maximum sum rate at the receiver and are optionally constrained to be orthonormal to each other. According to the characteristics of feedback information described above, we now take into account three feedback protocols: full feedback, partial feedback, and hybrid feedback protocols. The information of the kth user for feedback signaling is given as

$$F_{A,k} = \{g_k, \{\gamma_{\mathrm{M},k,m}\}_{m=1}^{M_t}\}$$
$$F_{B,k} = \{g_k, m_\mathrm{S}, \gamma_{\mathrm{M},k,m_\mathrm{S}}\}$$

which represents the full feedback and the partial feedback protocols, respectively, where g_k is the index of the set of the selected vectors, and $\{\gamma_{\mathrm{M},k,m}\}$ are the received SINRs estimated at the receiver based on g_k. Note that all $\{\gamma_{\mathrm{M},k,m}\}_m$ denote the post-decoding SINRs based on the MMSE reception. To reduce the burden of feedback, $F_{B,k}$ contains the maximum SINR $\gamma_{\mathrm{M},k,m_s}$ as well as its index m_s, instead of SINRs for all vectors, where

$$\gamma_{\mathrm{M},k,m_\mathrm{S}} = \max_{m=1,\ldots,M_t}\gamma_{\mathrm{M},k,m}$$

In practice, the feedback protocol $F_{B,k}$ is organized as follows. One bit is used to specify g_k, two bits denote m_s, and five bits are assigned to $\gamma_{\mathrm{M},k,ms}$. The last five bits are used for the SINR feedback signaling in the

HSDPA specifications [1]. The protocol for hybrid feedback is given as

$$F_{C,k} = \{g_k, m_S, \gamma_{M,k,m_S}, \{\gamma_{S,k,m}\}_{m \neq m_S}\}$$

where SINRs are included for both MMSE and SIC receiver structures (i.e., $\gamma_{M,k,ms}$ and $\gamma_{S,k,m}$, respectively).

Scheduling for Advanced Receivers

We exploit scheduling schemes employing user diversity for MIMO systems when advanced receivers, i.e., SIC receivers, are utilized, and propose the effective hybrid scheduling methods for such systems. In [19] two basic scheduling methods have been considered. The first assumes all the transmit antennas to be assigned to a single user selected based on the single user multiplexing methods, applied to PARC. Regardless of a receiver structure (whether SIC or not), its capacity is expressed as

$$C_A = \max_k \sum_m c_f(\gamma_{k,m})$$

For the second method, is that all users compete independently for each transmit antenna as a means to enhance overall system performance. The capacity of this scheme heavily depends on a particular receiver structure so that it is expressed as

$$C_{B,1} = \max_Q \sum_m \min_{k \in Q_m} c_f(\gamma_{S,k,m}),$$

$$C_{B,2} = \sum_m \max_k c_f(\gamma_{M,k,m})$$

for SIC receivers and linear receivers, respectively, where Q is a possible sub-set of all users, Q_m+1 is deflated version of Q_m in which the user after decoding at the mth layer has been zeroed, and $Q_1 = Q_m$. To achieve the maximum capacity through advanced receivers, hybrid schedulers can be used. One of hybrid schedulers, suggested in [20], is given by

$$C_{H,1} = \max\{C_A, C_{B,2}\}$$

in which both metrics of C_A with SIC receivers and $C_{B,2}$ with linear receivers are used to select the proper user. It is seen in [20] that only one metric is sufficient for the hybrid scheduling if we simply switch the scheduling policies between C_A and $C_{B,2}$ after the threshold point determined by the number of scheduled users. In practice, it is desirable to choose the point K_{sw} satisfying **E**$\{C_A\}$ = **E**$\{C_{B,2}\}$, so that the rule of the modified hybrid scheduler is then

$$C_{H,2} = \begin{cases} C_A, & K \leq K_{SW} \\ C_{B,2}, & K > K_{SW} \end{cases}.$$

Since it is often difficult to perfectly know how many users are to be scheduled before the activation of the scheduling method, we propose the hybrid scheme in which reception is to be constrained as single user SIC (SU-SIC), which is given by

$$C_{H,3} = \max_{\{S_j\}} \sum_j \max_k \sum_{m \in S_j} c_f(\gamma_{H,k,m})$$

where $\gamma_{H,k,m}$ is an element of SINRs, and S_j denotes the jth sub-group of transmit antennas. SU-SIC which is optimal in terms of sum-rate capacity cancels out only self interference, not multiuser interference, while SIC is conventionally designed to remove all interference. The optimality can be easily proven using the theorem in [21].

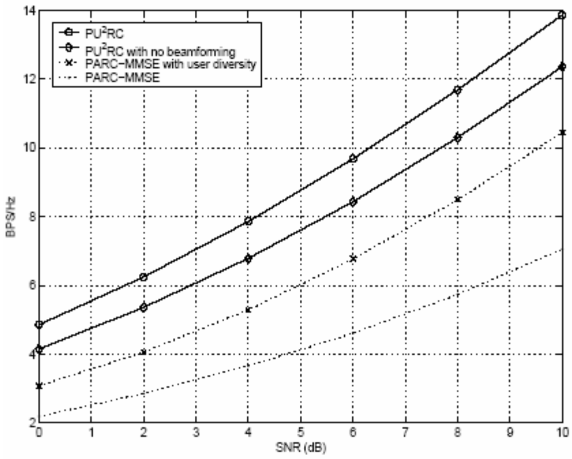

Figure 2. Throughput comparison of PU^{2}RC and PARC-MMSE

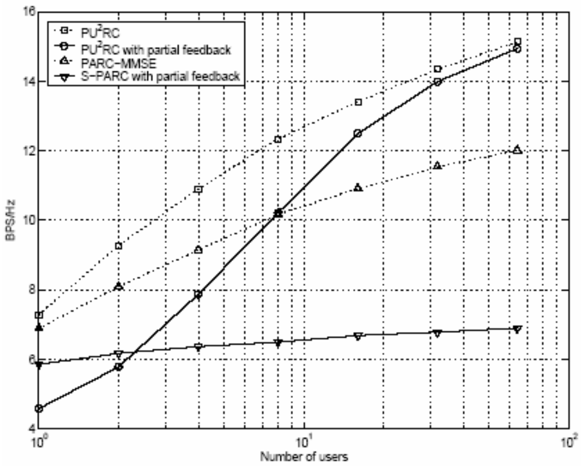

Figure 3. Throughput comparison of PU^{2}RC, PARC-MMSE, and S-PARC

Results

This section shows the results of computer simulations conducted for the performance evaluations with the schemes described in the previous sections. In all simulations, we assume that $M_t = M_r = 4$, linear receivers are used for both PU^{2}RC, PARC with MMSE linear receiver (PARC-MMSE), and SIC receivers are used for PARC. In Fig. 2, it is shown that the proposed scheme outperforms PARC-MMSE because the PU^{2}RC has about 2dB transmit beamforming gain with a 4-bit feedback over the system without it, i.e., PU^{2}RC with no beamforming, and achieves additional user diversity gain over PARC-MMSE with and without user diversity of about 3.5dB and 7dB, respectively. The additional user diversity gain comes from the spatial domain, which is not exploited in PARC schemes. The number of users is assumed to be $K = 10$. In Fig. 3, we show the performance of PU^{2}RC with partial feedback.

In Figs. 3 and 4, we illustrate results in terms of the number of users at average SNR = 10dB, and a 1-bit feedback used in PU^{2}RC for transmit beamforming. PU^{2}RC outperforms PARC-MMSE when feedback information for all transmit antennas is transmitted from user terminals back to the base station (BS). If partial feedback is used, i.e., the SINR of the selected basis or antenna vector, there is still a significant gain over S-PARC. This is because with partial feedback, S-PARC only exploits one transmit antenna, which results in a limited capacity gain over the number of users, while PU^{2}RC can transmit as many data streams as transmit antennas at its maximum. In Fig. 4, the throughput performance with hybrid scheduling is examined. It shows that when the number of users is less than 7, the performance of PARC, using SIC receivers, is better than that of PU^{2}RC, but rather surprisingly for higher number of users PU^{2}RC with linear receivers works better. As expected from this result, the hybrid scheduling scheme performs better than both PU^{2}RC and PARC, independent of the number of users. Note that the performances of all schemes are upper bounded by PU^{2}RC with optimal beamforming.

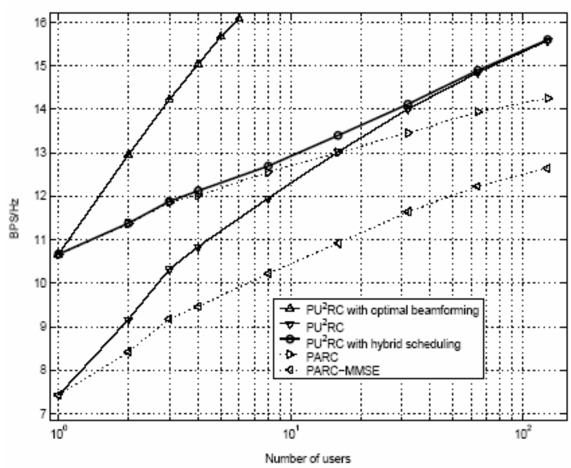

Figure 4. Throughput performance of PU^{2}RC with hybrid scheduling

Conclusion

In this paper, we proposed the advanced MIMO scheme using hybrid scheduling algorithm for 3GPP HSDPA. We investigated two categorized transmission methods such as SU-MIMO and PU^{2}RC for MU-MIMO. The proposed scheme has practical advantages, which are the reduction of receiver complexity and the amount of feedback. For future work, the efficient resource allocation scheme is required for SU-MIMO and MU-MIMO communications with feedback signaling. Moreover, spatial channel modeling needs to be combined together with the above MIMO schemes for fair comparisons in real system environments.

ACKNOWLEDGMENT

The authors would like to thank Seung-Yong Park, Kiho Kim, R. W. Heath, Jr., D. Gesbert, and Jianjun Li for their comments, as well as 3GPP MIMO delegates for their valuable discussions during the working group meetings (http://www.3gpp.org).

This paper has been supported in part by the Samsung Advanced Institute of Technology (SAIT) and in part by National Research Laboratory (NRL) program.

REFERENCES

[1] R. Love, A. Ghosh, R. Nikides, L. Jalloul, M. Cudak, and B. Classon, "High Speed Downlink Packet Access Performance," in *Proc. IEEE VTC 2001*, May 2001, pp. 2234–2238.

[2] I. E. Telatar, "Capacity of multi-antenna gaussian channels," tech. rep., *AT&T Bell Laboratories Internal Technical Memorandum 1995*, published in *the European Transactions on Telecommunications*, Nov./Dec. 1999.

[3] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[4] M. Sharif and B. Hassibi, "A comparison of time-sharing, DPC, and beamforming for MIMO broadcast channels with many users," *submitted to IEEE Trans. Commun.*, 2004.

[5] E. N. Onggosanusi, A. G. Dabak, and T. A. Schmidl, "High rate space-time block coded scheme: performance and improvement in correlated fading channels," in Proc. *IEEE WCNC 2002*, vol. 1, Mar. 2002, pp. 194–199.

[6] G. J. Foschini, "Layerd space-time architecture for wireless communication in a fading environment when using multiple antennas," *Bell Labs Technical Journal*, vol. 1, no. 2, pp. 41–59, 1996.

[7] *3GPP TR 25.876*, "Multiple-input multiple-output in UTRA," in 3GPP, Feb. 2004.

[8] L. U. Choi and R.D. Murch, "A transmit preprocessing technique for multiuser MIMO systems using a decomposition approach," in *IEEE Transactions on Communications*, vol. 3, pp. 20–24, Jan. 2004.

[9] Q. H. Spencer, A.L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," in *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 52, pp. 461–471, Feb. 2004.

[10] Z. Tu and R.S. Blum, "Multiuser diversity for a dirty paper approach," in *IEEE Communications Letters*, vol. 7, pp. 370–372, Aug. 2003.

[11] W. Yu and W. Rhee, "Degrees of freedom in multi-user spatial multiplex systems with multiple antennas," in *IEEE Transactions on Communications*, 2004, submitted for Publication.

[12] P. Viswanath, D.N.C Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," in *IEEE Trans. Inform. Theory*, vol. 48, pp. 1277–1294, 2002.

[13] H. Viswanathan and K. Kumaran, "Rate scheduling in multiple antenna downlink wireless systems," in *Proc. Allerton Conference on Communications and Control*, Oct. 2001.

[14] Lucent, "Increasing MIMO throughput with PARC," in *3GPP*, R1(01)0879, Aug. 2001.

[15] Ericsson, "Selective per antenna rate control," in *3GPP*, R1(04)0307, Feb. 2004.

[16] D. J. Love, R. W. Heath, and T. Strohmer, "Grassmannian Beamforming for Multiple-Input Multiple-Output Wireless Systems," *IEEE Transactions on Information Theory*, vol. 49, pp. 2735-2747, Oct. 2003.

[17] Samsung, "The performance of TxAA in some HSDPA environments," in *3GPP*, R1(02)1129/1214/1380, Aug.–Nov. 2002.

[18] Samsung, "Per-user unitary rate control (PU^2RC)," in *3GPP*, R1(03)0586, May 2003.

[19] R. W. Heath, M. Airy, and A. J. Paulraj, "Multiuser diversity for MIMO wireless systems with linear receivers," in *Proc. Asilomar Conf. Signals, Systems, and Computers*, Pacific Grove, CA, Nov. 2001, pp. 1194–1199.

[20] S. Kim, H. Kim, C. S. Park, and K. B. Lee, "Space-Time Technique for Wireless Multiuser MIMO Systems with SIC Receivers," in *Proc IEEE PIMRC 2004*, Sep. 2004.

[21] N. Jindal, S. Vishwanath, and A. Goldsmith, "On the Duality of Gaussian Multiple-Access and Broadcast Channels," *IEEE Trans. on Information Theory*, vol. 50, No. 5, May 2004, pp. 768–783.

James S. Kim (S'04) was born in Korea in 1969. He obtained his Bachelor and Master of Engineering degree in Electronics and Communications Engineering from the College of Engineering, Hanyang University, Korea in 1994 and in 2000, respectively.

He is now pursuing his Doctor of Philosophy in the School of Electrical Engineering, Seoul National University, Seoul, Korea. In February 1994 he joined the Comm. and Network Lab, Samsung Advanced Institute of Technology, and he is now a senior member of technical research staff. Since 1999, he has been the Editor-in-Chief of 3GPP (WCDMA standard) Transmit Diversity TR.

His research interests include the areas of multi-user information theory (MIT), multiple-input and multiple-output (MIMO), transmit diversity (TxD), wireless scheduling and adaptive signal processing for 3G evolution and 4G wireless communications.
(e-mail:kimsj@mobile.snu.ac.kr, and communication@samsung.com)

Antonio Forenza (S'04) received his B.S. and M.S. degrees in Telecommunications Engineering from Politecnico di Torino (Italy), and the diploma of specialization in Mobile Communications Engineering from Institut Eurécom, Sophia Antipolis (France), in 2001. He is currently pursuing a Ph.D. program in Electrical

Engineering at The University of Texas at Austin (Texas, USA).

In 2001 he interned as systems engineer at Iospan Wireless, Inc., San Jose, CA, a startup company developing high-speed fixed wireless system, based on MIMO-OFDM technology. His main research focus was on link-adaptation and physical layer algorithms design. In the fall 2001 he joined ArrayComm, Inc., San Jose, CA, a startup company deploying adaptive smart antenna technology for standard and proprietary high-speed wireless communications systems. As systems research engineer he contributed to the intellectual property of the company as well as developed DSP software for the WCDMA 3G wireless platform. Over the summer 2004 he interned as research engineer at Samsung Advanced Institute of Technology (SAIT), Suwon, Korea, contributing to the intellectual property of the company as well as being actively involved in the standardization activities for 3GPP, IEEE 802.11n and IEEE 802.16. In September 2003 he joined The University of Texas at Austin where he's currently serving as Ph.D. student and researcher.

His research interests include wireless MIMO-OFDM and WCDMA systems, smart antenna signal processing, adaptive link and physical layer transmission techniques, MIMO antenna design, interference cancellation in MU-MIMO.
(e-mail: forenza@ece.utexas.edu)

Marios Kountouris (S'05) received his Diploma in Electrical and Computer Engineering from the National Technical University of Athens, Greece, 2002, and his M.Sc in Digital Communications from Ecole Nationale Superieure des Telecommunications (E.N.S.T Paris), France, in 2004. In November 2004, he joined the Eurecom Institute (Sophia-Antipolis, France) where he is currently pursuing his Ph.D in Electrical Engineering.

Over the summer 2004 he interned as research engineer at Samsung Advanced Institute of Technology (SAIT), Suwon, Korea, working on reconfigurable MIMO-OFDM systems as well as multiuser scheduling. In parallel, he was actively involved in the standardization activities for 3GPP, and IEEE 802.16. From November 2004, he is with France Telecom R&D, Paris, working on adaptive transmission schemes for multi-user MIMO systems

His general interests lie in the areas of multi-user communications, information theory and signal processing. Current research focuses on adaptive link and physical layer transmission techniques, scheduling and resource allocation, interference cancellation in MU-MIMO systems, and MIMO-OFDM systems.
(e-mail: marios.kountouris@eurecom.fr)

Hojin Kim (M'05) received his Bachelor of Science in Electrical and Computer Engineering from Purdue University, Indiana in 1997. He received his Master of Science from the Electrical and Computer Engineering at the University of Florida, Florida in 2000.

In 2000, he was with LG electronics institute of technology as a research engineer. Since 2001, he has been a research engineer at Samsung advanced institute of technology. His research interests include MIMO, OFDM, adaptive transmission and 3GPP standardization.

Chang Soon Park (S'02) received the B.A.Sc. and M.Eng. degrees from the School of Electrical Engineering and Computer Science, Seoul National University, Seoul 151-742, Korea, in 2000 and 2002, respectively,

He is now pursuing his Doctor of Philosophy in the School of Electrical Engineering and Computer Science, Seoul National University, Seoul 151-742, Korea
(e-mail: parkcs@mobile.snu.ac.kr)

Ashish Pandharipande (M'99) was born in India, in 1977. He pursued his graduate education at the University of Iowa, where he obtained a doctoral degree in Electrical and Computer Engineering in 2002, a Masters degrees in Mathematics in 2001, and a Masters degree in Electrical and Computer Engineering in 2000. He received his Bachelors degree in Electronics and Communication Engineering in 1998 from the College of Engineering, Osmania University, India.

His current research interests are in Reconfigurable wireless communications and signal processing algorithms, and cross-layer design.
(e-mail: p.ashish@samsung.com)

Kwang Bok Lee (M'90-SM'03) received the B.A.Sc. and M.Eng. degrees from the University of Toronto, Toronto, Ont., Canada, in 1982 and 1986, respectively, and the Ph.D. degree from McMaster University, Canada in 1990. He was with Motorola Canada from 1982 to 1985, and Motorola USA from 1990 to 1996 as a Senior Staff Engineer.

At Motorola, he was involved in the research and development of wireless communication systems. He was with Bell-Northern Research, Canada, from 1989 to 1990. In March 1996, he joined the School of Electrical Engineering, Seoul National University, Seoul, Korea. Currently he is an Associate Professor in the School of Electrical Engineering. He was a Vice Chair of the School of Electrical Engineering from 2000 to 2002. He has been serving as a Consultant to a number of wireless industries. Since 2003, he has been a senior member of the IEEE.

His research interests include mobile communications, communication technique covering physical layer and upper layer. He holds ten U.S. patents and four Korean patents, and has a number of patents pending. He was an Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, Wireless Series in 2001, and has been an Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS since 2002. And he is a co-chair of the ICC2005 Wireless Communication Symposium. He received the Best Paper Award from CDMA International Conference 2000 (CIC 2000), and the Best Teacher Award in 2003 from College of engineering, Seoul National University.
(e-mail: klee@snu.ac.kr)