Toward a Reconfigurable MIMO Downlink Air Interface and Radio Resource Management: The SURFACE Concept

István Zsolt Kovács, Nokia Siemens Networks

Luis García Ordóñez, Universitat Politècnica de Catalunya

Miguel Navarro, Aalborg University

Eduard Calvo, University of Navarra

Javier Rodríguez Fonollosa, Universitat Politècnica de Catalunya

ABSTRACT

This article presents a reconfigurable multiple-input multiple-output air interface design combined with radio resource management algorithms applicable to multi-user MIMO transmission in downlink orthogonal frequency-division multiple access systems. A low-complexity, adaptive, and channel-aware single-user and multi-user MIMO transmission solution is proposed based on the findings of the SURFACE European Commission funded research project. The resulting cross-layer design covers the reconfigurable air interface, and practical layer 1 and layer 2 RRM mechanisms for time-frequency packet scheduling. System-level performance analysis, including the effects of limited and imperfect feedback from the terminals, shows that the SURFACE air interface provides an attractive practical solution for operations with high-rate adaptive MIMO transmission schemes in the context of next-generation wireless communication systems.

INTRODUCTION

In the near future, due to the fostering of new and interactive multimedia mobile services, prospective wireless systems are likely to face highly heterogeneous traffic requirements. Hence, such systems will have to provide not only high spectral efficiency downlink access but also radio resource management (RRM) strategies for highly adaptive multi-antenna transmission schemes. A means of achieving these objectives is to investigate a general and reconfigurable air interface solution, which, ruled by upper layers' requirements and constraints, is able to adapt the physical layer (PHY) setup and the usage of the network resources to align its operation mode with the quality of service (QoS) requirements of the served mobile devices. In this respect, the design of RRM algorithms to ensure that the radio resources are efficiently utilized given the available channel state information (CSI), becomes a key step toward a new generation of wireless communication systems.

Multiple-input multiple-output (MIMO) transmission with orthogonal frequency-division multiple access (OFDMA) seems to be the best positioned system architecture, as indicated by several cooperative research studies (e.g., MASCOT [1], and WINNER [2]), and standardization processes such as those conducted by the Third Generation Partnership Project (3GPP) for Universal Mobile Telecommunications System (UMTS) terrestrial radio access network (UTRAN) Long Term Evolution (LTE) [3, 4] and IEEE for WiMAX [5]. The MIMO OFDMA framework poses new challenges and opportunities for RRM in order to meet the system performance targets for a variety of different services and radio environments. While MIMO transmission schemes open the spatial domain frontier, pursuing the realization of multiplexing and diversity gains, OFDMA provides the RRM algorithms with the capability of assigning system resources based on time-frequency units (physical resource blocks, PRBs) comprising a discrete number of temporal (OFDM symbols) and frequency (subcarriers) units. Consequently, the MIMO OFDMA framework allows the served devices to be multiplexed in the time-frequency and space domains whenever multi-user (MU) techniques are used. Most of the MU PHY and RRM algorithms proposed so far in the open literature are, however, quite involved requiring in practice a very large signaling overhead and exhaustive search algorithms in order to form the MU terminal pairs and/or adapt the MIMO transmission mode [6–8].

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The Self-Configurable Air Interface (SURFACE) European Commission (EC) funded project [9] aims at studying and evaluating the performance of such an evolved air interface capable of self-reconfiguring based on channel and traffic knowledge in order to satisfy global network QoS requirements. The fundamental ingredients toward this main objective are a wise combination of extensive theoretical research with the practical constraints ensuring the implementation. This article presents a high-level description of the SURFACE air interface concept for downlink (DL) MIMO OFDMA systems. Compared to the previous literature on MU-MIMO PHY/RRM, our proposed solution aims to integrate an already existing OFDMA PHY/RRM framework, rather than redesigning it. This allows us to investigate the benefits but also the implications of introducing the MU-MIMO degree of freedom into the air interface.

In this study we include mechanisms that are traditionally part of the RRM functions such as hybrid automatic repeat request (HARQ) and fast link adaptation (LA), but most effort is dedicated to develop the proposed single-user/multiuser (SU-/MU-) MIMO adaptation and practical time-frequency packet scheduler (PS). Their performance is evaluated through extensive MU system-level simulations in a typical homogeneous microcell scenario, taking into account limitations due to practical system design aspects, including the channel estimation errors, channel quality indicator (CQI) imperfections, and uplink feedback delays. Although the OFDMA time-frequency PHY from 3GPP LTE Release 8 frequency-division duplexing [3, 4] is adopted here as a case study, most of the discussions in this article are directly applicable to any other MIMO OFDMA system with time-frequency scheduling capabilities, such as WiMAX.

The rest of the article is structured as follows. The next section contains the proposed SURFACE air interface concept and describes the corresponding main RRM blocks, their functionality, and related modeling aspects. We then cover the system-level performance evaluation. After presenting the simulation assumptions, the results obtained for representative RRM settings in combination with several MIMO transmission schemes are discussed. The main conclusions from this study are summarized in the final section.

SURFACE Evolved Air Interface Concept

RRM Framework and PHY Setup

The RRM framework contains the family of optimization techniques which ensure that radio resources are efficiently utilized at the base station (BS) when serving users according to their QoS attributes. Traditionally, this includes algorithms from layer 1 to layer 3. The RRM functions at layer 3, however, are considered to be semi-dynamic mechanisms, since they are mainly executed during the setup of new data flows or during infrequent reconfigurations. On the contrary, the RRM algorithms at layers 1 and 2 involve dynamic decisions at the BS based on the feedback information reported by the scheduled mobile stations (MSs) [10]. These functionalities, shown in the block diagram in Fig. 1, are precisely the ones modeled and analyzed in our work.

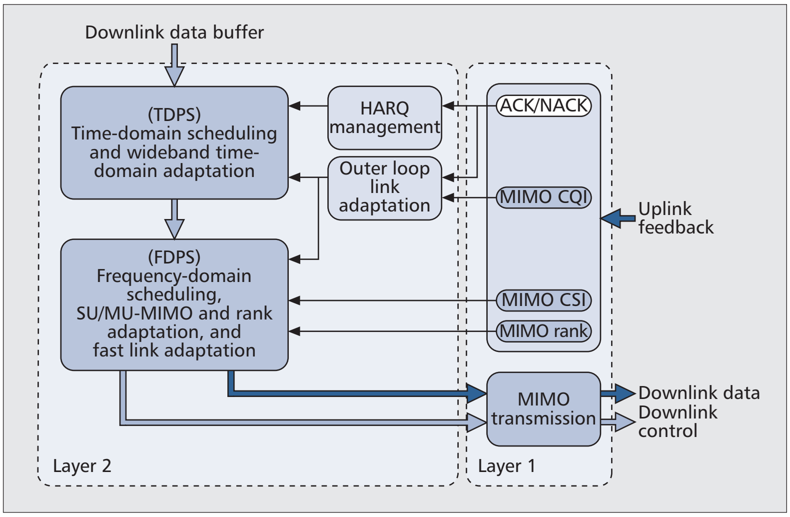

Figure 1. *Block diagram of the downlink MIMO-aware RRM with SU/MU mode adaptation. The blocks and feedback signaling analyzed in this article are highlighted in dark blue.*

The OFDMA RRM framework supporting the proposed SURFACE reconfigurable MU-MIMO air interface is built on top of the general packet scheduling and link adaptation solution presented in [10, 11] and already studied in the context of traditional single-user MIMO transmission schemes [12]. Every transmission time interval (TTI), the RRM performs scheduling decisions by allocating PRBs to the users, and link adaptation decisions by assigning a modulation and coding scheme (MCS). Hence, a close interaction is needed between the PS and the HARQ manager, as it is responsible for scheduling retransmissions, and also between the inner loop and the outer loop LA unit, which controls the block error rate of first transmissions based on positive or negative HARQ acknowledgments (ACK/NACK) from past transmissions [10]. As illustrated in Fig. 1, the PS is decomposed into a time-domain scheduler (TDPS), which selects the users to be scheduled in the next TTI, and a frequency-domain scheduler (FDPS), which allocates PRBs to the selected users. QoS awareness is introduced into and controlled by the TDPS, while the radio-channel-aware FDPS exploits frequency-selective fading by scheduling users primarily on the PRBs with high channel quality [10, 11]. Such a solution provides an attractive trade-off between performance and complexity, and also allows integrated consideration of scheduling limitations due to control channels. Performance studies of downlink OFDMA systems using a 20 MHz bandwidth and single-input multiple-output (SIMO) transmission show that a time and frequency domain packet scheduling algorithm can yield gains in both average system capacity and cell-edge data rates on the order of 35–40 percent [11]. This performance, however, depends significantly on the frequency-domain scheduling resolution, the accuracy of the CSI

Parameter	Setting/Value
Carrier frequency	2 GHz
Transmission bandwidth	10 MHz
Number of active subcarriers	600
TTI duration	1 ms
Sub-carriers per PRB	12 sub-carriers = 180 kHz
OFDM symbols per TTI	11 data + 3 control
Modulation schemes	QPSK, 16-QAM, 64-QAM

Table 1. *SURFACE PHY setup.*

available at the BS via the feedback information from the MS, as well as the type of user traffic served.

The SURFACE RRM sketched in Fig. 1 is designed following the principles described in [10, 11] with an optimized FDPS, which includes additional PS/LA stages to accommodate the newly introduced MU-MIMO transmission schemes. Thus, this RRM framework allows, independently for each of the served terminals, a two-fold MIMO adaptation: the classical SU-MIMO rank adaptation and the additional SU/MU reconfiguration, all based on the channel conditions and feedback information from the terminals. The following sections describe in more detail the adopted MIMO and RRM improvements.

The SURFACE OFDMA PHY setup is strongly based on the OFDMA time-frequency PHY from 3GPP LTE Release 8 frequency-division duplexing [3, 4] and is summarized in Table 1. These system parameters have been selected for reference, although the 3GPP LTE Release 8 specifications do not allow the direct implementation of our proposed MIMO scheme. Thus, the main target of our proposed adaptive MIMO and RRM schemes are future 3GPP LTE Advanced systems.

MIMO Transmission Schemes

To date, multi-user MIMO schemes operating close to the maximum achievable rates of MIMO downlink channels are largely derived within an information-theoretic context and rely on the dirty paper coding (DPC) technique. However, DPC is extremely computationally demanding and cannot be implemented in practice. There has been much research devoted to obtaining simpler schemes that mimic the DPC concept with lower complexity requirements, lattice coding being the most promising one. The simplest (one-dimensional) lattice encoder is Tomlison-Harashima precoding (THP), which is an appealing technique due to its low complexity and the fact that it is able to retain a large fraction of the gains promised by DPC. On the other hand, it has not been shown that DPC-like techniques are necessary for achieving most of the capacity. In practical cases when processing complexity must be minimized, we can resort to traditional linear techniques (i.e., precoding or beamforming) [8]. In our case we focus on zero-forcing beamforming (ZFBF), which is known to exhibit lower sensitivity to errors in channel state knowledge.

Both ZFBF and THP are suitable transmissions techniques for MU transmission. However, when spatial multiplexing of multiple users is not feasible (e.g., due to ill-conditioning of the resulting aggregate channel matrix and/or nonoptimal total served throughput), an SU-MIMO technique may still be used to provide multiplexing and diversity gains for the terminals. For this case, we consider a singular value decomposition (SVD)-based precoding scheme that can establish several spatial streams, the number of which is denoted as transmission rank.

The MIMO adaptation mechanism provides different downlink transmission possibilities by choosing between MU and SU, and adapting the transmission rank when SU transmission is selected. Within the SURFACE concept we assume that the same MCS and the same MIMO transmission rank are used on all PRBs allocated to a given terminal per TTI. Although this restriction certainly lowers the achievable system performance compared to a full time-frequency MIMO adaptive case, it results in more practical transmission schemes and lower-complexity RRM algorithms. The proposed MIMO adaptation is possible to be implemented based on the feedback information from the served terminals, as described next.

MIMO Feedback from Terminals

An efficient structure for the layer 1 and 2 control signaling information is essential in order to maximize the throughput enhancement of downlink MIMO transmission. Feedback overhead, including precoding information as well as the channel quality indicator (CQI) and its granularity in the time and frequency domain, ACK/NACK, MIMO transmission rank, and so on, should be aggressively minimized while keeping the system performances within desired limits. Furthermore, the adopted MIMO transmission algorithms also have an impact on the selection of the HARQ mechanism to be used and the resulting behavior [9, D4.2]. Hence, practical MIMO schemes need to be carefully evaluated with LA and time-frequency domain PS techniques for optimal network performance. In terms of update/reporting rate, the CQI and HARQ information are potentially the most demanding (0.5–20 ms) [10, 11]. The precoding information, on the contrary, can be reported at a lower rate (50 ms), while the MIMO transmission rank can be updated at a very slow rate (100 ms) in a semi-static way [12].

The minimum required feedback from the terminals in order for the BS to perform the proposed DL MIMO-aware RRM comprises (Fig. 1):

- *MIMO CQI* providing direct (e.g., signal-to-interference-plus-noise ratio [SINR]) or indirect (e.g., MCS) information on the average channel conditions estimated on individual or groups of PRBs
- *MIMO rank* denoting the optimum number spatial streams to be used for the next transmission

Parameter	Setting/value
Cellular scenario	SURFACE microcell [9]
Number of terminals per cell	5, 10, 20, 50
Channel model	WINNER/3GPP SCME-D correlated [2]
Base station transmitter	2 or 4 antenna elements according to SCM-D model [2]
Terminal receiver	2 antenna elements according to SCM-D model [2] LMMSE per stream
Terminal velocity	3 km/h
Terminal maximum SINR	25 dB
Terminal noise figure	9 dB
MIMO OFDMA PHY	See Table 1
MIMO CQI feedback	2 × PRB resolution Includes 1 dB measurement & quantization errors 2 TTI time-delay and 5 TTI reporting period
MIMO CSI feedback	2 × PRB resolution. Error-free 2 TTI time-delay and 5 TTI reporting period
Traffc model	Infinite queue/buffer
MIMO LA	See "MIMO Link Adaptation" section
MIMO PS	See "SU/MU MIMO Packet Scheduling" section

Table 2. *Downlink system-level assumptions and simulation parameters.*

Multi-user MIMO schemes operating close to the maximum achievable rates of MIMO downlink channels are largely derived within an information-theoretic context and rely on the DPC technique. However, DPC is extremely computationally demanding and cannot be implemented in practice.

- *MIMO CSI* as the right singular vectors matrix from the SVD decomposition of the estimated average MIMO channel per group of consecutive PRBs
- *HARQ information* indicating the reception status (ACK/NACK) of the transmitted data packets

The baseline CQI, rank, and HARQ feedback information is assumed to be determined by the terminal following the standardized system design and is modeled here according to the 3GPP LTE Release 8 [3, 4]; we further adopt the main system-level assumptions used in [12] and summarized in Table 2. The corresponding practical feedback design and modeling aspects have been addressed in literature and are available, for instance, in [10–12]. Within the SURFACE concept, the optimum MIMO transmission rank is a wideband measure; that is, it is obtained based on the instantaneous channel conditions on all available PRBs. The adopted MIMO HARQ scheme and related feedback are described in [11], and, due to the across-stream coding scheme, only one HARQ chain per terminal is needed to control the transmission in all SU/MU-MIMO transmission modes. The CQI-CSI reports are calculated for each group of two consecutive PRBs (360 kHz) and are ready for use at the BS with a time delay of 2 TTI (2 ms), including both the time it takes to send the reports and the time to decode them at the BS. For simplicity, a periodic reporting scheme with a period of 5 TTI (5 ms) is employed in this study [9, D4.2 and D5]. We further assume that the scheduling information and CQI-CSI reports are always received correctly at the served MS and serving BS, respectively.

MIMO Link Adaptation

The optimized operation of the MIMO transmission schemes introduced earlier requires, in addition to the classical fast LA (selection of the optimal MCS), a MIMO rank adaptation mechanism. In general, when closed-loop MIMO schemes are used, the MIMO rank selection procedure involves estimating the total achievable throughput with the adopted precoding schemes and each possible rank. In our case, the optimum transmission rank is selected at the terminal side based on the SVD decomposition of the average (over 2 × PRB) channel with the objective of maximizing the user throughput. The CQI estimated for this optimal channel rank is then reported to the BS, and used in the PS/LA to configure the next transmission. Observe that the CQI-CSI feedback is needed at the BS to perform the correct user orthogonalization in MU mode or stream orthogonalization in SU mode. The terminals do not, however, derive, estimate, or feed back any MU-MIMO-specific information to the serving BS. Instead, the new RRM functionalities described in the next section use solely SU-MIMO specific feedback information to perform both SU- and MU-

We propose to use a proportional fair metric, expressed as the ratio between the sum of estimated instantaneous throughputs and the sum of average delivered past throughputs corresponding to the selected MU-MS pair.

MIMO resource allocation. This is one of the main features of the proposed adaptive SURFACE MIMO transmission scheme and renders the re-configuration of the air interface more transparent to the terminals, thus minimizing the required control plane signaling.

Previous investigations in scenarios with low-mobility terminals have disclosed the influence on the overall system performance of the rate at which the MIMO adaptation is performed. In this study we adopt the quasi-dynamic MIMO scheme with adaptation only on the first HARQ transmissions [12], as a trade-off solution between the fast-adaptive (per TTI) and semi-static wideband SINR-based (per 5–10 ms) schemes.

SU/MU MIMO Packet Scheduling

The SURFACE PS mechanism is based on the proportional fair scheduling metric in both time and frequency domains, and includes the ability to schedule, in MU-MIMO mode, a selected group of terminals. This procedure, however, must be completely based on SU-MIMO measures, since the terminals do not feedback any MU-specific information to the serving BS, as described previously. The proposed SU/MU-MIMO scheduling algorithm contains three main steps:

- *Step 1*: Identify the candidate set of terminals to be potentially grouped for MU transmission.
- *Step 2*: Identify which frequency resources should/can be used for MU transmission, and select the MU-MS pairs.
- *Step 3*: Select the final MU-MS pairs to be scheduled using the same PS algorithm as for SU-MIMO MSs.

There are several proposals for how to implement and optimize the PS steps listed above in the literature. However, as mentioned earlier, here we aim for a more practical design solution, which can reuse most of the features of a previously developed time-frequency packet scheduler [10, 12] in combination with more advanced schemes such as the ones envisioned for next-generation wireless communication systems. In the following, we develop our proposal for the SU/MU-MIMO PS algorithm.

In *Step 1* we simply identify the set of terminals with first HARQ transmission and a given preferred MIMO rank (i.e., only single-stream, only multi-stream, or any number of streams). This algorithm is in-line with the time and frequency granularity of the original SU-MIMO adaptation; as such, Step 1 is considered part of the time-domain PS. Furthermore, when only the rank-1 (single-stream) terminals are selected, the algorithm avoids the need for additional rank adaptation in the frequency domain PS, as both SU-MIMO and MU-MIMO transmission are scheduled in rank-1 mode for these terminals.

Step 2 is part of the frequency-domain PS. A straightforward strategy for selecting the SU/MU-MIMO transmission mode is to maximize the total throughput on the scheduled PRBs. This implies the verification of all possible MU-MS pairs on each available PRB, which can be highly computationally demanding, depending on the maximum number of terminals allowed to be scheduled per TTI. In order to reduce the computational complexity in the FDPS, we use instead a simple sorting algorithm to find the N_{MU} best MSs on each PRB by ranking them based on their reported CQI. As a result, only these N_{MU} MU-MS pairs have to be verified on each PRB. The resulting MaxCQI criterion inherently provides higher potential for MU orthogonalization due to the similarly good channel conditions of the two MSs. Nevertheless, the mechanism to select the MU-MS pairs additionally estimates a measure of orthogonality of the preferred precoding vectors (MIMO-CSI) for the selected N_{MU} MSs, before the actual MU-MIMO technique (THP or ZFBF) is applied. The final decision on the SU/MU-MIMO transmission mode is made by comparing the expected aggregate user throughput in MU-MIMO mode with the SU throughput expected for the MS with the highest CQI in the selected group of N_{MU} MSs. To further account for the non-ideal MU channel orthogonalization after the MU-MIMO precoding, a certain CQI degradation factor for each MS in the MU-MS pair can be included in the previous calculation. For simplicity, in our study we adopt $N_{MU} = 2$ and a CQI degradation of 3 dB, although in practice these are system parameters that can be adjusted based on other system-wide design considerations.

Step 3 requires the definition of an MU scheduling metric per PRB in order to make the final frequency-domain PS step unaware of the MIMO transmission mode. Here we propose to use a proportional fair metric, expressed as the ratio between the sum of estimated instantaneous throughputs and the sum of average delivered past throughputs corresponding to the selected MU-MS pair.

System-Level Results and Discussions

General Simulation Settings and Assumptions

In order to evaluate the performance of the presented SU/MU MIMO RRM algorithms and MIMO transmission schemes considered in the SURFACE air interface concept, detailed multicell system-level simulations have been carried out in a low-mobility scenario within a frequency reuse 1 network consisting of a total of 19 cells under the 3GPP SCM-D MIMO correlated channel model [2]. The MSs are uniformly distributed in the entire simulation area with 50 percent outdoor and 50 percent indoor user location, and only the MSs connected to the center BS are simulated with full RRM. All terminals in the center cell are assumed to be active, have low mobility (3 km/h), and utilize the same set of MIMO transmission modes, with 2 × 2 or 4 × 2 antenna configurations. The interfering cells are considered to operate at full load and the interference signal is obtained at the receiving terminal based on the assumption that it originates from a MIMO rank-1 transmission with the same number of transmit antennas. The main simulation parameters and assumptions are summarized in Table 2.

The presented system-level results are the most representative ones from the findings in the SURFACE project. Detailed descriptions and further results can be found in [9, D2.1, D5, D6, and D7.4], while the corresponding link-level results have been presented in [13]. The performance metrics analyzed in the following are average cell spectral efficiency (SE), cell-edge SE (or 5 percent outage SE), and number of users scheduled per TTI. These performance measures are investigated and discussed with a varying number of active terminals per cell (user diversity order [UDO]).

LINK-LEVEL MU-MIMO PERFORMANCE

The goodput per PRB vs. SINR performance curves obtained for the adopted SU- and MU-MIMO 2 × 2 schemes are presented in Fig. 2, corresponding to a first transmission block error rate (BLER) target of 20 percent. The single-stream SU-MIMO and ZFBF-based MU-MIMO performance show similar performances, whereas the multi-stream SU-MIMO performance is approximately 1 dB better in the entire SINR range due to its double coding block length (over the two streams) with respect to the corresponding single stream (rank-1) SS transmission [13]. The THP-based MU-MIMO results show approximately 1.5 dB performance degradation in the low-SINR regime compared to the SU-MIMO case, and this performance gap gradually decreases with increasing SINR so that in the high-SINR regime both ZFBF and THP yield the same performance [6]. The latter result is a direct consequence of the sensitivity of the THP-based precoding scheme on the quality of the channel state information and experienced SINR [13]. Recent studies have shown that it is possible to further optimize the linear precoding schemes based on the characteristics of the signal constellations used while maintaining good performance under imperfect CSI assumptions [8].

REFERENCE SU-MIMO PERFORMANCE

As a reference for the evaluation of the SURFACE air interface concept with SU/MU adaptation, in Fig. 3 we give the main system performance results obtained using only SU-MIMO transmission schemes. These results show the expected trend of system-level gains when switching between the different MIMO configurations. It is worth noticing, however, that all transmission schemes are robust relative to the system load (UDO) in terms of the achievable average cell spectral efficiency, which proves the effectiveness of the PHY/RRM algorithms used. The second main observation is that both the 2 × 2 and 4 × 2 SU-MIMO transmission modes yield a large variation in the number of actual scheduled MS per TTI depending on the UDO. Furthermore, even for high UDO (i.e., high cell load), a low average number of scheduled terminals per TTI (between 2 and 4) is achieved. This result can be explained by the low capacity of adaptation to the experienced cell load when only SU-MIMO transmission schemes are utilized. For an efficient scheduler design, however, it is highly desirable to maximize the number of scheduled terminals per TTI regardless of the cell load and the adopted MIMO transmission scheme. As we show next, this can actually be achieved by introducing MU-MIMO transmission schemes and the corresponding MIMO RRM mechanisms described in the previous section.

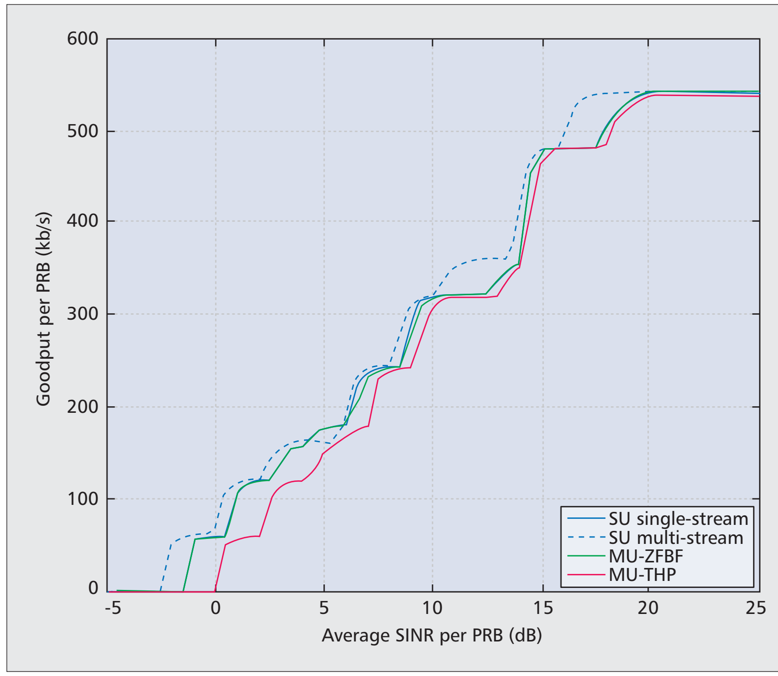

Figure 2. *System-level goodput per PRB with BLER target of 20 percent vs. SINR for the SU- and MU-MIMO 2 × 2 transmission schemes.*

ADAPTIVE SU/MU MIMO PERFORMANCE

In Fig. 4 we show the performance results for the 2 × 2 and 4 × 2 SU/MU-MIMO ZFBF-based and 2 × 2 SU/MU-MIMO THP-based transmission schemes. Comparing the gain of the MU-MIMO ZFBF schemes with the corresponding SU-MIMO reference cases in Fig. 3 we can observe the same range of 10–15 percent improvement in the cell spectral efficiency when switching from the 2 × 2 to the 4 × 2 antenna configuration. Independent of the cell load, the cell edge performance is only marginally impacted by the used MU-MIMO scheme, since the SU-MIMO transmission mode is largely selected for these low-channel SINR terminals. Under the adopted infinite queue/buffer traffic model, this system-level gain comes mostly from being able to schedule an increased number of users per TTI at the price of sacrificing user fairness and reducing peak user throughputs. For the finite queue/buffer traffic model case, on the contrary, the cell performance was shown to be significantly lower while providing increased peak user throughputs with a low number of users scheduled per TTI [9, D7.4].

Comparing the ZFBF-based and THP-based results in Fig. 4, as expected, an overall better cell performance is obtained with the THP-based scheme. The cell edge system performance is only slightly improved with the THP-based scheme, and this is a direct consequence of the link-level performance differences discussed earlier, but also of the MaxCQI algorithm used for

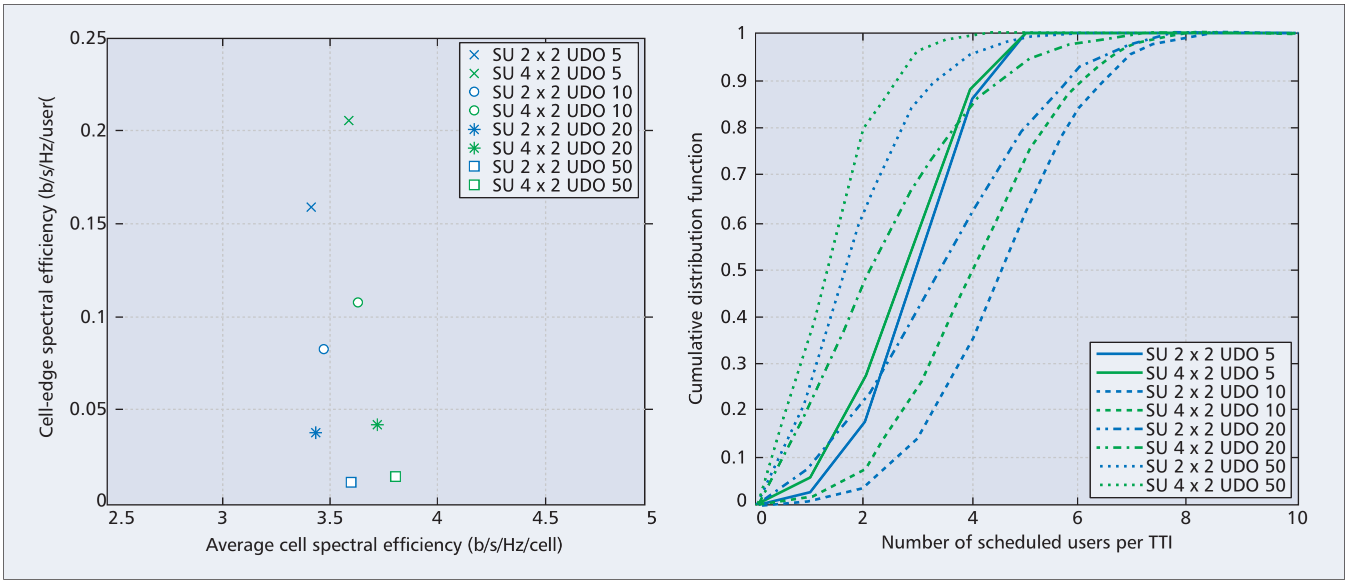

Figure 3. *System performance results for the SURFACE SU-MIMO transmission scheme with varying cell load: spectral efficiency (left) and number of scheduled users per TTI (right).*

preselecting the MU-MIMO MS. It is also important to stress the efficiency of the user scheduling algorithm in terms of the number of simultaneously scheduled users (Fig. 4, right): except for the very low load case (UDO = 5), the average number of users scheduled per TTI has been doubled compared to the case of using only SU-MIMO transmissions (Fig. 3, right). This leaves more freedom for further QoS control mechanisms and more realistic user traffic handling. Furthermore, the range of the number of scheduled terminals per TTI has also been reduced compared to the SU-MIMO cases, indicating improved utilization of system resources.

Conclusions

The successful deployment of next-generation wireless systems strongly relies on the development and implementation of advanced SU-/MU-MIMO transmission techniques, as indicated by the large ongoing effort in the standardization processes conducted by the 3GPP and IEEE. This article has illustrated how advanced SU-MIMO and MU-MIMO schemes can be efficiently combined with practical time-frequency packet scheduling mechanisms to harness most of the potential gain in multiple-antenna cellular systems. Although fast link adaptation, and adaptive bit and power loading also play a critical role, it is also highly desirable to have the ability to schedule in MU transmission mode, while, at the same time, keeping to minimum the signaling requirements and the need for terminal reconfiguration. The presented SURFACE air interface concept implements this RRM framework and SU-/MU-MIMO reconfigurability mechanism with low complexity and without requiring MU-specific feedback from the terminals. Based on the adopted assumptions in the system design, we have shown that the proposed SU/MU-MIMO adaptation is particularly beneficial in high-load scenarios with more than 10 active users per cell. Although not presented in this article, the user traffic type turned out to also have a clear impact on the achievable system performance, and the proposed jointly optimized PHY/RRM MIMO solution proved to successfully adapt to the expected heterogeneous traffic in the cell.

Acknowledgment

This work has been partly funded by the IST-2006-027187 FP6 STREP "Self Configurable Air Interface" (SURFACE) project, and by the Spanish Science and Technology Commissions and FEDER funds from the EC (TEC2006-06481/TCM and CONSOLIDER INGENIO CSD2008-00010 COMONSENS).

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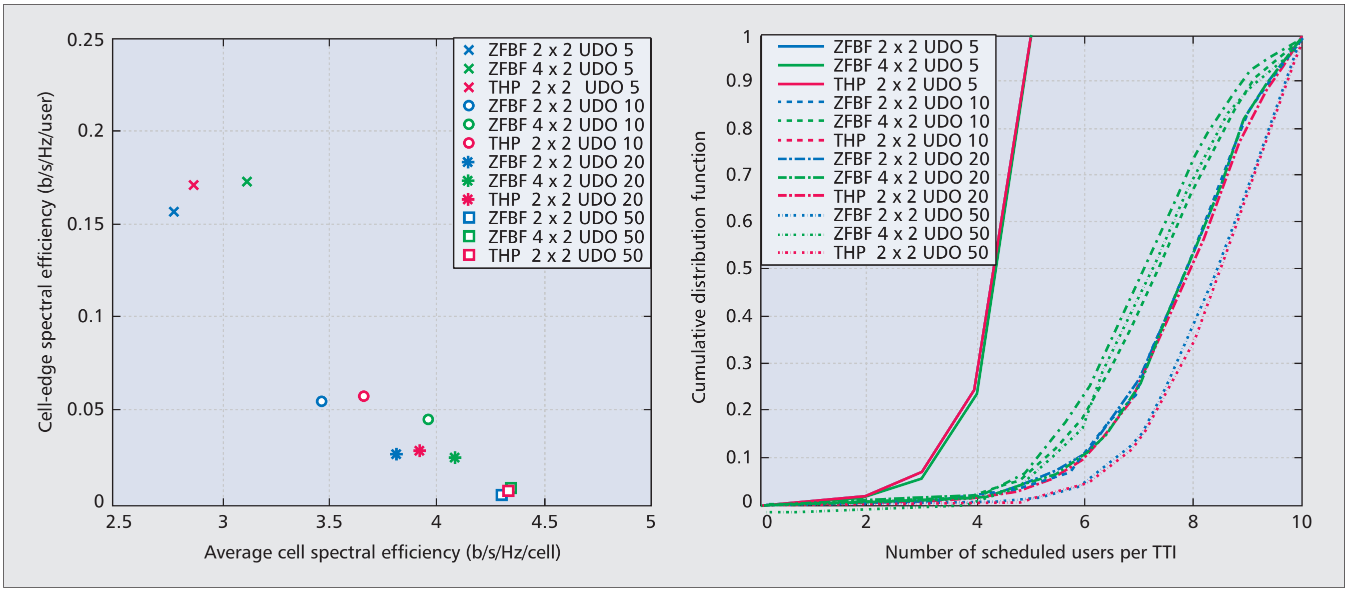

Figure 4. *System performance results for the SURFACE SU/MU-MIMO transmission schemes with varying cell load: spectral efficiency (left) and number of scheduled users per TTI (right).*

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BIOGRAPHIES

ISTVAN ZSOLT KOVACS (istvan.kovacs@nsn.com) has received his B.Sc. from "Politehnica" Technical University of Timisoara, Romania in 1989, his M.Sc.E.E. from the Franco-Polish School of New Information and Communication Technologies/Ecole Nationale Supérieure des Télécommunications de Bretagne, Poland/France, in 1996, and his Ph.D.E.E. in wireless communications from Aalborg University, Denmark, in 2002. From 2002 to August 2005 he held the position of assistant research professor with Center For TeleInFrastruktur, Department of Communication Technology of Aalborg University, in the Antennas and Propagation division. Currently he has the position of wireless networks specialist with Nokia Siemens Networks, Aalborg, Denmark, where he conducts system-level studies and radio resource management research for multiple-input multiple-output transmission schemes within UTRAN LTE, LTE-Advanced, and ITU IMT-Advanced systems.

LUIS GARCIA ORDOÑEZ (luis.garcia-ordonez@upc.edu)[M] received his electrical engineering and Ph.D. degrees from the Universitat Politècnica de Catalunya (UPC) — Barcelona Tech in 2003 and 2009, respectively. He conducted his Ph.D. at the Department of Signal Theory and Communications of UPC, where he now holds a postdoctoral research associate position. From 2001 to 2008 he participated in the European IST projects I-METRA, NEXWAY, and SURFACE. Currently he is involved in the CONSOLIDER-INGENIO project COMONSENS on Foundations and Methodologies for Future Communication and Sensor Networks. His research is devoted to studying the performance limits of wireless MIMO systems from the information-theoretic and communication points of view.

MIGUEL NAVARRO (mn@es.aau.dk) is at Aalborg University.

EDUARD CALVO [S] (ECalvo@iese.edu) received M.S. and Ph.D. degrees (with highest honors) in electrical engineering from the Universitat Politècnica de Catalunya (UPC) — Barcelona Tech in 2004 and 2009, respectively. In 2009 he joined the IESE Business School, University of Navarra, as an assistant professor in the Department of Production, Technology, and Operations Management. He has participated in several European projects from the 6th and 7th Framework Program. During 2004 and 2008, he held research appointments at the Massachusetts Institute of Technology. His research interests lie in the intersection of information theory, optimization theory, statistical signal processing, and their applications to wireless and underwater communication networks, and operations research. He was given the Salvà i Campillo award to the Best Young Engineer by the Guild of Electrical Engineers of Catalonia in 2005.

JAVIER RODRIGUEZ FONOLLOSA [SM] (javier.fonollosa@upc.edu) is a professor in the Department of Signal Theory and Communications of Universitat Politècnica de Catalunya — Barcelona Tech. Since March 2010 he is manager of the Communications and Electronic Technologies (TEC) area of the National Research Plan of Spain. He is the author of more than 100 papers in the area of signal processing and communications. Since 1995 he has played a very active role in EC funded projects related to MIMO systems in UMTS and Systems beyond 3G. In 1995 he led UPC's participation in the projects TSUNAMI(II) and SUNBEAM. From January 2000 until December 2008 he acted as project coordinator of the projects METRA, I-METRA, and SURFACE. He has also been actively engaged in the National Research Plan of Spain. Since October 2006 he is project coordinator of the Type C project Fundamental Bounds in Network Information Theory, and since December 2008 he is project coordinator of the CONSOLIDER-INGENIO project COMONSENS on Foundations and Methodologies for Future Communication and Sensor Networks, a five-year €3.5 million effort of 86 researchers belonging to 10 universities and research centers in Spain. In June 1995 and September 2001 he was Co-Chairman and organizer of the IEEE Signal Processing/ATHOS Workshop on Higher-Order Statistics, Begur, Girona, Spain, and the IST Mobile Communications Summit 2001, Sitges, Barcelona, Spain. He was elected a member of the Signal Processing for Communications (SPCOM) Technical Committee of the IEEE Signal Processing Society in January 1999. He received his Ph.D. degree from Northeastern University in 1992.