



A Reconfigurable Downlink Air Interface: Design, Simulation Methodology, and Performance Evaluation

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Abstract: We aim at studying the performance of a novel generalised air interface capable of self-adapting in order to satisfy global network quality of service requirements based on channel and traffic knowledge. Pursuing this objective, reconfigurable transmission strategies but also L2 radio resource allocation methods and packet scheduling policies have been surveyed within the MIMO-OFDMA framework for the downlink channel of a wireless broadband cellular system. This paper introduces the proposed air interface, describes the adopted simulation methodology, and summarizes the first performance evaluation results. Regarding methodology, we focus on practical simulation structures enabling statistically reliable results with minimum complexity. Concerning physical layer aspects, a detailed description of the parameters and transmit/receive strategies considered is given such that our research results are reproducible.

Keywords: downlink, broadband wireless, OFDMA, MIMO, channel aware, resource allocation, packet scheduling, simulation methodology

1. Introduction

Due to the fostering of new, interactive multimedia mobile services, prospective cellular systems are likely to face highly asymmetrical rate requirements by the user terminals in the near future. Hence, such systems will have to provide high-throughput downlink access, overcoming bandwidth scarcity by using high spectral efficiency techniques involving the physical layer (PHY) operation but also packet scheduling (PS) and radio resource management strategies. A means of linking this objective with network-wide needs is to investigate the general formulation and performance characterization of a reconfigurable air interface which, ruled by upper layers' needs, is able to adapt the PHY setup and the usage of the network resources to align its operation mode with the current quality of service (QoS) requirements. This is the focus of the SURFACE (Self-Configurable Air Interface) FP6 project [1].

The design of resource allocation (RA) and PS strategies able to match the instantaneous channel conditions is prominent for the achievement of high spectral efficiencies (throughput). Imperfections in the channel state knowledge limits the ultimate PHY performance and constrains the PHY and RA/PS techniques to be applied. The implementation and design of such techniques, that needs to resort to the MIMO framework, is applied in combination with the OFDMA access mode, whose advantages over other designs are numerous. To mention but a few, OFDMA can be efficiently implemented through FFT/IFFT, is multipath robust, and provides the L2 RA-PS with the capability of assigning system resources based on time-frequency chunks (physical resource

blocks, PRBs) comprising a discrete number of temporal (OFDM symbols) and frequency (subcarriers) units. Using OFDMA, users can be multiplexed in both time and frequency. Additionally, they can be multiplexed also in the space domain pursuing the realization of multiplexing and diversity gains (when possible) using MIMO. To explore whether multiuser (MU) transmission over the same bandwidth is advantageous as compared to multi-stream single-user (SU) transmission, in this paper we have investigated the performance of MU dithered zero-forcing Tomlinson-Harashima precoding (THP) [2], MU zero-forcing beamforming (ZFBF) [3], and SU minimum BER linear transceiver designs (minBER) [4].

On the other hand, users' QoS requirements arising from different service specifications prevent us from allocating the limited radio resources of the cell for throughput maximization purposes only, and hence fairness constraints are imposed on their use. We aim at optimizing the system performance under a loose cross-layer approach that allows us to capture the gains from link adaptation while formulating the overall design within a general, flexible framework. This framework allows us to evaluate performance of the proposed air interface by applying a simulation methodology entailing two simulation planes, the link simulation plane and the system simulation plane, and one interface, the link-to-system (L2S) interface. The link simulation plane deals with PHY aspects, whereas the system simulation plane targets both physical and data link layer issues. In particular, it outputs performance results based on system-level key parameter indicators (KPIs) and enables benchmarking against the results obtained in similar scenarios with reference air-interface solutions, e.g. the 3GPP UTRAN Long Term Evolution (LTE) [5] and the WINNER IST project [6].

Concerned with the implementation of an efficient, QoS-aware, self-configurable air interface, our contributions towards this objective are the following. First, we propose a loose cross-layer approach which decouples the L2 PS from the channel state information and eases the task of the RA. Second, we survey different SU/MU-MIMO transmission strategies and analyze them under a unified perspective which facilitates comparison. Finally, a practical simulation methodology is proposed in order to enable performance evaluation of the air interface.

The structure of this paper is as follows. Section 2 deals with the proposed loose cross-layer approach and addresses the design of the L2 PS and RA. The MIMO air interface is characterized in Section 3, where fair comparison of different transmit strategies is provided. Following, Section 4 describes the simulation methodology adopted for performance evaluation, and some preliminary results are included in Section 5. To conclude, some summarizing remarks are sketched in Section 6.

2. A Loose Cross-Layer Approach

The achievement of the highest possible system spectral efficiency satisfying the QoS constraints depends on the suitability of the PHY transmission technique and of the resource allocation (RA) and PS algorithms for the actual degree and accuracy of channel knowledge at both sides of the link. The approach of this work is cross-layer in essence since both the PHY and the MAC layers are optimized jointly. However, to lighten the complexity load at the transmission end and reduce the channel state information exchange between the terminals and the network, we proposed to adopt a loose cross-layer approach still capturing most of the gains associated to non-independent layer optimization. In our approach, the PS and RA are designed independently under the following paradigm [7], conceptually shown in Figure 1. It consists of:

- *A priority-based PS* - The L2 PS dynamically monitors delays and queue lengths and assigns numerical priorities to the different data flows to be multiplexed regardless of the channel conditions, [8][9].

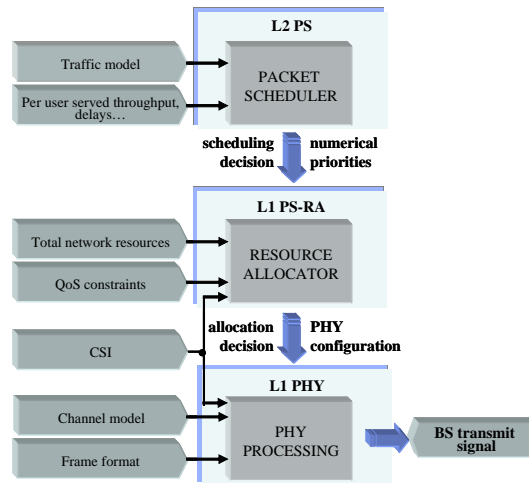


Figure 1: Block diagram of the transmitter employing the proposed loose cross-layer L1-L2 RA-PS approach.

- A QoS-oriented RA - Given the flow priorities at some time instant, an underlying channel-aware L1 PS-RA solves an optimization problem to either maximize a weighted sum (using the priorities) of the users' rates or guarantee some (possibly different) bit rate (GBR) for all of them. In the former case, QoS is implemented by means of complying with a differentiated maximum uncoded symbol-error rate ($maxSER$) [10] or bit-error rate ($maxBER$) [11] (strategies that aim at satisfying some pre-specified coded block error rate target). By utilizing perfect or partial channel state information (CSI) from the terminals in the network, the RA optimizes the resource global allocation among all terminals while satisfying the QoS needs of each terminal individually.

The separation of the L2 PS and L1 PS-RA allows the RA to be adjusted according to the channel conditions, while the scheduler can be independently chosen from a variety of existing designs according to the required fairness, delay, and/or other QoS constraints depending upon the service type or higher layer needs.

3. MIMO Air Interface

To date, schemes operating close to the maximum achievable rates of MIMO downlink channels are largely information-theoretic and rely on the dirty paper coding (DPC) technique [12][13]. However, DPC is extremely computationally demanding and cannot be implemented directly in practice. Among all the simpler schemes that mimic the DPC concept with lower complexity requirements, the most promising one is lattice coding [14][15]. The simplest (one-dimensional) lattice encoder is THP [7], which results appealing due to its low complexity and the fact that it is able to retain a large fraction of the gains promised by DPC. However, if we cannot afford high processing complexity, we can resort to traditional linear techniques, i.e., precoding or beamforming. In particular, we shall focus on ZFBF, which is known to exhibit low sensitivity to errors in the knowledge of the channel state.

Both ZFBF and THP are suitable for MU transmission over one PRB, where the user selection, the power allocation, and the MCS are decided by the L2 PS and the L1 PS-RA. However, if multiple users cannot be properly paired up for MU-MIMO transmission, e.g., due to ill-conditioning of the resulting aggregate channel matrix and/or non-optimal total served throughput, a SU-MIMO technique may still be used to provide multiplexing and diversity gains. In this situations we propose to consider the minimum BER linear MIMO transceiver design of [4]. Since both ZFBF and THP are MU techniques based on the orthogonalization of the users' transmission, in case of perfect CSI at both sides of the link the MU transmissions are fully decoupled into parallel SU transmissions. This allows us to

obtain simple input/output analytical expressions which lighten the complexity of subsequent simulations.

The number of antennas at the BS and at each of the user terminals is denoted by n_T and n_R , respectively. Consider the simultaneous transmission to K single-antenna users within one PRB, where we define $\mathbf{H} = [\mathbf{h}_1 \mathbf{h}_2 \dots \mathbf{h}_K]^T \in \mathbb{C}^{K \times n_T}$ as the aggregate channel matrix, where \mathbf{h}_k is the channel response as seen by the k -th user. In case of SU *minBER* transmission, $\mathbf{H} \in \mathbb{C}^{n_R \times n_T}$ will denote the SU channel matrix and K shall stand for the number of active substreams. The transmitted and estimated symbols intended for the k -th user are denoted by s_k and \hat{s}_k , respectively, and s_k is assumed to be drawn from a square M_k -QAM constellation. We define snr as the per subcarrier *pre*-signal to noise ratio, which neglects the channel effect and is obtained as the ratio between the user transmit power on one subcarrier and the corresponding noise power on that subcarrier.

3.1. MU-THP

Dithered zero-forcing THP is based on the QR decomposition of the aggregate channel matrix, $\mathbf{H} = \mathbf{G}\mathbf{Q}$, where \mathbf{G} is lower triangular and \mathbf{Q} is unitary. By defining $g_k \triangleq [\mathbf{G}]_{k,k}$, the following closed-form input-output relation applies

$$\hat{s}_k = \begin{cases} (s_k + z_k) \bmod 4 & M_k = 2 \\ (s_k + z_k) \bmod 2\sqrt{M_k} & M_k > 2 \end{cases}, \quad (1)$$

where z_k is the equivalent noise and admits the following expression, where equality is *in distribution*,

$$z_k = \begin{cases} \frac{\mathcal{U}_{[-1,1]} + g_k \sqrt{\frac{2}{3}} \text{snr} \mathcal{N}(0,1)}{|g_k|^2 \text{snr} + 1/2} & M_k = 2 \\ \frac{\sqrt{M_k} (\mathcal{U}_{[-1,1]} + j \mathcal{U}_{[-1,1]} + g_k \sqrt{\frac{2}{3}} \text{snr} \mathcal{C}\mathcal{N}(0,1))}{|g_k|^2 \text{snr} + 1} & M_k > 2 \end{cases}. \quad (2)$$

While $\mathcal{U}_{[a,b]}$ denotes a r.v. with uniform distribution on the interval $[a, b]$, $a \bmod b$ denotes the unique representation of the real and imaginary parts of a over the interval $[-b/2, b/2]$.

3.2. MU-ZFBF

In ZFBF, the channel dependency is condensed into the parameter $\alpha_H \triangleq \text{trace}\{(\mathbf{H}\mathbf{H}^H)^{-1}\}$, and it follows that $\hat{s}_k = \frac{\text{snr}s_k + z_k}{\text{snr} + \alpha_H/K}$. Again, z_k is equivalent noise which can be generated *in distribution* as

$$z_k = \begin{cases} \sqrt{\frac{\alpha_H}{K} \text{snr}} \mathcal{N}(0, 0.5) & M_k = 2 \\ \sqrt{\frac{2}{3}} (M_k - 1) \frac{\alpha_H}{K} \text{snr} \mathcal{C}\mathcal{N}(0, 1) & M_k > 2 \end{cases}. \quad (3)$$

3.3. SU-minBER

In a nutshell, the minBER scheme performs the SVD of the channel matrix \mathbf{H} and transmits a rotated version of K symbols through the K strongest eigenmodes such that the relative performance of each of the symbols is the same. This scheme optimizes performance for any fixed transmission rate when equal constellations are used on all the selected channel eigenmodes. If λ_i denotes the square of the i -th singular value of \mathbf{H} , the input-output relation of this scheme is as simple as $\hat{s}_k = s_k + \frac{1}{\sqrt{\rho}} \mathcal{C}\mathcal{N}(0, 1)$, where

$$\rho = \begin{cases} \left[\frac{1}{K} \sum_{i=1}^K \left(\lambda_i \frac{\text{snr}}{K} + 1 \right)^{-1} \right]^{-1} - 1 & M_k = 2 \\ \left[\frac{1}{K} \sum_{i=1}^K \left(\lambda_i \frac{2}{3} (M_k - 1) \frac{\text{snr}}{K} + 1 \right)^{-1} \right]^{-1} - 1 & M_k > 2 \end{cases}. \quad (4)$$

4. Simulation Methodology

4.1 Methodology

Our target is to employ a suitable simulation framework enabling meaningful, statistically significant link and system level performance evaluation of the proposed air interface at minimum computational complexity. Inevitably, this brings about the decoupling of the link and system simulations, giving rise to the structure in Figure 2.

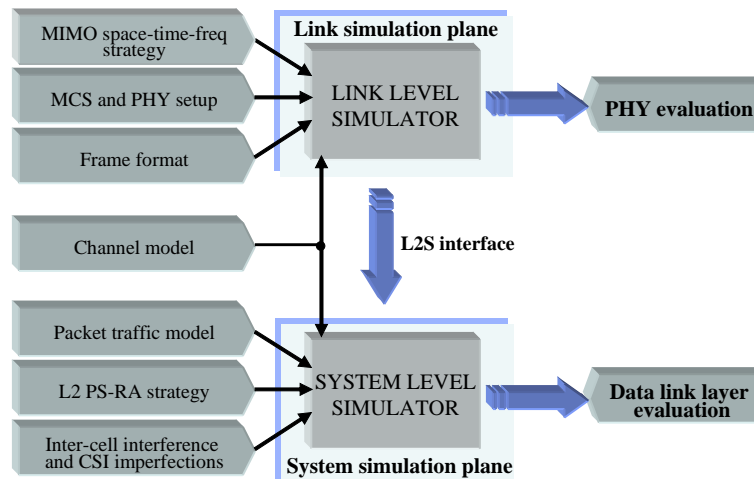


Figure 2: Structure of the global simulator for the proposed air interface and RA-PS schemes.

- *Link simulation plane* – It is responsible for characterizing the per-PRB instantaneous PHY performance assuming that the PS has chosen some user/s to transmit using one (or more) PRBs, and that some network resources have been devoted to its (their) transmission. It subsumes the impact of the channel model, the tx/rx technique, and of the MCS into a block error rate (BLER) measure such that deciding transmission success at the system-level is greatly simplified. The link level simulation procedure is explained in [16], where some simplifying assumptions were considered to reduce the number of degrees of freedom to be explored.
- *System simulation plane* – The system level simulator extends the performance evaluation of the link-level by accommodating the L2 PS-RA algorithms to investigate the performance of DLC features such as fast scheduling (in the time, frequency, and/or space domain), and fast link adaptation. Practical constraints regarding the amount and quality of the CSI are also implemented at this level.
- *L2S interface* – A simplified model that describes the performance of each PHY setup versus a link quality measure is implemented by resorting to the Exponential Effective SINR Model (EESM) [16] and the use of the associated look-up tables generated from the link-level BLER vs. SINR results. For a summary of these techniques refer to [6].

4.2 Link and system parameters

The link and system parameters for these SU/MU-MIMO evaluations have been selected in accordance to the current air-interface concept developed in SURFACE and are based on the 3GPP LTE specifications in order to allow benchmarking. The main structural blocks in Figure 2 employing these parameters are described in Table 1.

Table 1: Description of the structural blocks involved in the simulation process of Figure 2.

Structural Block	Description
MIMO space-time-freq strategy	MU-THP or MU-ZFBF or SU-minBER
MCS and PHY setup	BPSK (rates 1/2 and 2/3), QPSK and 16QAM (rates 1/2, 2/3, and 3/4), and 64QAM (rates 2/3 and 3/4)
Frame format	10 MHz BW (0.9 BW efficiency) comprising 50 PRBs. 1PRB = 14 OFDM symbols (1 ms) and 12 consecutive subcarriers (180 kHz). Control channel and pilot (reference) overhead included in the throughput calculations. A Hybrid Automatic Repeat Request (HARQ) mechanism is also implemented [13][14][15]. Coding blocks of 3GPP rel. 6 turbo code ECR 1/3 [22] span either a short block (2 PRBs) or a long block (12 PRBs). The 3GPP interleaver [23] is used.
Channel model	Based on the WINNER II SCM [20] and the 3GPP LTE MicroCell path-loss models [12]. Distance-dependent path loss, antenna radiation and shadow fading characteristics included at system level.
Packet traffic model	The input data traffic of each served terminal is simulated as a continuous stream with always full data buffer.
L1/L2 PS-RA strategy	L2 PS: channel unaware scheduling. L1 PS-RA: TD/FD PS (possibly PF) and QoS-oriented RA (either maxSER or maxBER) [7].
Intercell interference	Full load traffic scenario, i.e., all interfering cells are transmitting at full power uniformly distributed in the simulation bandwidth.
CSI imperfections	CSI available for each PRB. The feedback model includes estimation errors, processing/tx delay, and reporting period.
Cellular layout	Urban Micro Cell deployment with the 19 hexagonal cells layout model used in 3GPP LTE Micro Cell specifications [21], but with an enlarged inter-site distance (ISD) of 350 m. Outdoor located omni-directional BS and outdoor-to-outdoor and outdoor-to-indoor scenarios are studied.

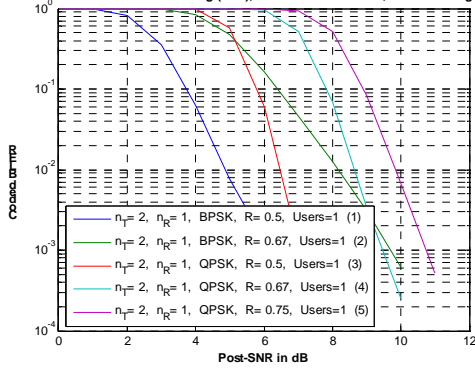
5. Preliminary Performance Evaluation

The evaluation of the performance of the proposed air interface amounts first to the simulation of the MIMO air interface at the link level. Figures 3 and 4 compare the short block performance of the proposed MIMO strategies in a *reference* scenario where the effect of the channel is neglected, i.e., $g_k = 1$ in (2), $\alpha_H = K$ in (3), and $\lambda_i = 1$ in (4). When real channel models are considered, the obtained performance is adjusted to these curves via EESM, and the information for the mapping between curves is kept for integration with system level simulations.

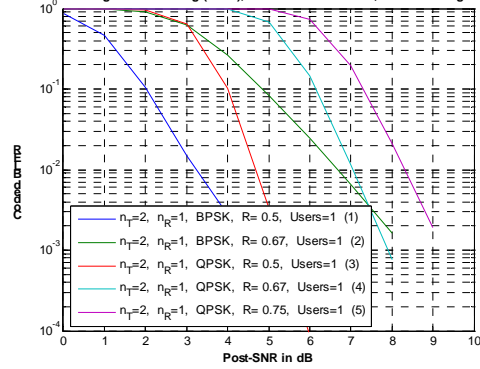
A 2x1 antenna configuration is assumed for MU transmission, whereas 2x2 is selected for SU transmission. Well-known synergies between the effective blocklength, the modulation format, and the coding rate are captured in Figures 3 and 4. In particular, it is shown that MCS configurations with higher modulation formats realize a larger slope of the BLER curve thanks to the coding gain of an implicitly larger blocklength.

As for the comparison of the proposed schemes, it can be seen that their reference performance is nearly equal. This is because the reference channel is the same for all of them. However, as true channel models are plug into the simulator, the different statistics of the channel-related parameters characterizing the performance of each technique will come into play showing quite different results. In particular, we expect THP to greatly outperform ZFBF, specially at low signal to noise ratios and large modulation formats.

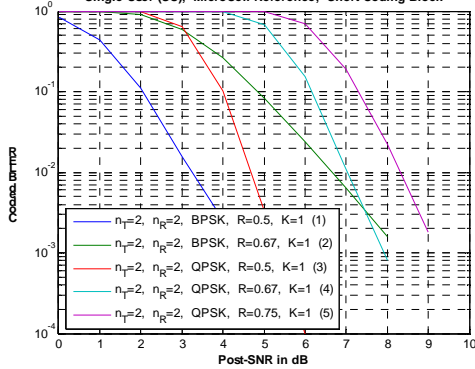
Tomlinson-Harashima Precoding (THP), MicroCell Reference, Short Coding Block



Zero-Forcing BeamForming (ZFBF), MicroCell Reference, Short Coding Block



Single-User (SU), MicroCell Reference, Short Coding Block



Single-User (SU), MicroCell Reference, Short Coding Block

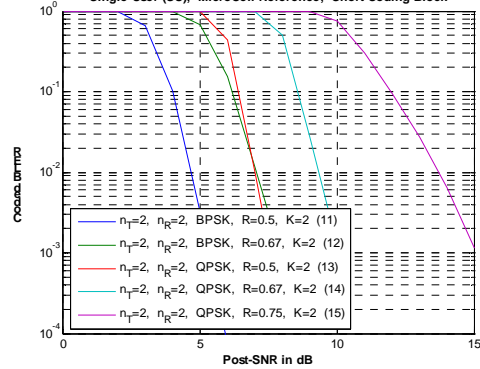
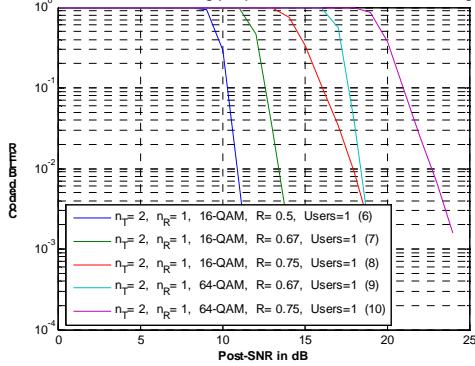
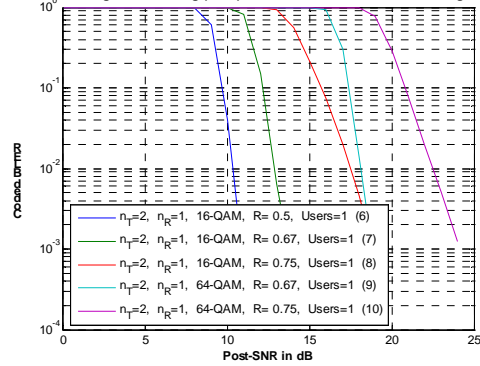


Figure 3: Coded BLER vs SNR curves for the first half of the MCS set.

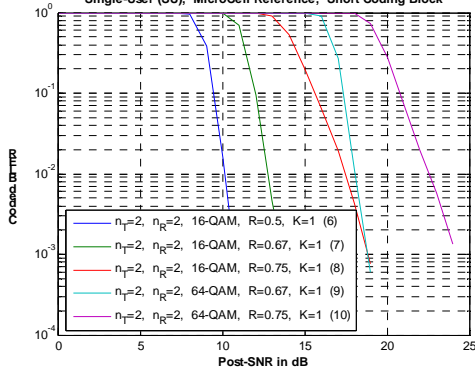
Tomlinson-Harashima Precoding (THP), MicroCell Reference, Short Coding Block



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Single-User (SU), MicroCell Reference, Short Coding Block



Single-User (SU), MicroCell Reference, Short Coding Block

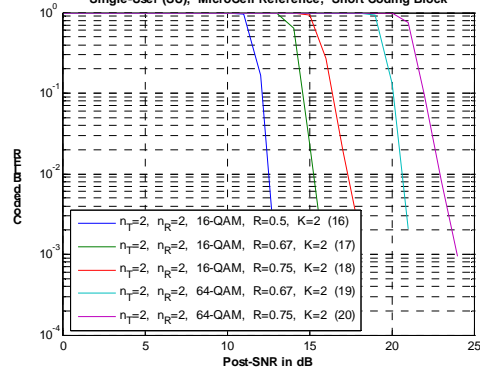


Figure 4: Coded BLER vs SNR curves for the second half of the MCS set.

6. Conclusions

We have identified air interface reconfigurability as a key feature enabling the dynamic fulfillment of global QoS requirements in the downlink of a cellular system. With respect to this, high spectral efficiency PHY strategies based on MIMO-OFDMA have been surveyed which, along with a loose cross-layer approach operating in a desirable point of the complexity-performance tradeoff has given rise to the proposal of an air interface. A simulation methodology for system performance evaluation has been proposed and preliminary link level results have been presented. The air interface evaluation at system level is being undertaken and will be presented in future publications.

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