PERFORMANCE AND MODELING OF LTE H-ARQ

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ABSTRACT

The 3rd Generation Partnership Project (3GPP)'s Release'8 Long Term Evolution (LTE) defines the next step of 3G technology. LTE offers significant improvements over previous technologies such as UMTS/HSPA. Higher downlink and uplink speeds, lower latency and simpler network architecture are among the new features that are provided. One of the central features that provides transmission robustness is hybrid-ARQ, which in LTE provides physical layer retransmission using incremental redundancy and soft combining.

In this paper we propose a low-complexity model based on AWGN link level simulations that is capable of reliably predicting the BLER improvement due to the use of incremental redundancy H-ARQ in LTE.

1. INTRODUCTION

The increase of mobile data usage, fueled by bandwidth demanding applications such as mobile TV, Web 2.0 and online gaming has led to the development and standardization of UTRA Long Term Evolution (LTE) [1]. LTE is intended to be a mobile-communication system that can take the telecom industry into the 2020s. LTE leaves legacy technology behind and sports a radio interface being purely optimized for IP transmissions and offering operators a high spectrum flexibility, supporting from 1.4 MHz to 20 MHz bands [2].

Also the core network is focused on the packed-switched domain, migrating away from the circuit-switched network. The System Architecture Evolution (SAE) core network architecture significantly enhances the core network performance while ensuring interoperability with previous networks such as High Speed Packet Access (HSPA). Hence LTE will be very convincing for network operators that already have HSPA networks running.

Several techniques have been used in order to provide significant improvements over its predecessor technologies. Improvements on the air interface include OFDMA in the downlink, SC-OFDMA in the uplink, and Multiple-Input Multiple Output (MIMO) enhancements, while on the network side the SAE provides an all-IP network capable of supporting higher throughput and lower latency. To be specific, user plane latency has been reduced to below 5 ms while supporting speeds of up to 350 km/h (500 km/h in some cases). As a result of these improvements, LTE is capable of offering download speeds of up to 100 Mbps and upload speeds of up to 50 Mbps within a 20 MHz spectrum [2].

Transmission integrity is guaranteed by the application of an hybrid automatic repeat request (H-ARQ) retransmission scheme, very similar to the one utilized in High Speed Downlink Packet Access (HSDPA). The performance of the retransmission handling strongly influences the performance of LTE both on the physical layer [3] as well as from a network perspective.

For performance evaluations, in particular on system-level, low-complexity models for the physical layer procedures are needed to keep the simulation times manageable. H-ARQ — since positioned on layer 1— has been of interest for modeling already for quite some time. For other technologies, e.g. HSDPA such models already exist [4] and have been utilized in a variety of applications [5, 6].

In this paper we focus on deriving a low-complexity model capable of accurately predicting the H-ARQ gains on the physical layer. Our model can be easily utilized in system-level simulations [7], thus allowing for the investigation of retransmission strategies in LTE networks. The paper is organized as follows: in Section 2 the LTE downlink shared channel will be introduced, after which we explain the principles of H-ARQ in Section 3. With these findings, we are able to derive our model, describing the simulation results, and its application in Section 4. Finally, Section 5 concludes the paper.

2. LTE DOWNLINK SHARED CHANNEL STRUCTURE

The LTE Downlink Shared Channel (DL-SCH) uses OFDM to mitigate frequency selectivity and to multiplex the resources for multiple users. The spectrum is divided in 15 kHz subcarriers (a 7.5 kHz spacing is also possible) and arranged in groups of twelve contiguous subcarriers each forming a Resource Block (RB) which are the basic schedulable unit in the frequency domain. For a 1.4 MHz downlink bandwidth space, six RBs are allocated, which we express as $N_{\mathrm{RB}}^{\mathrm{DL}} = 6$. Alternatively, for a bandwith of 20 MHz $N_{\mathrm{RB}}^{\mathrm{DL}} = 100$.

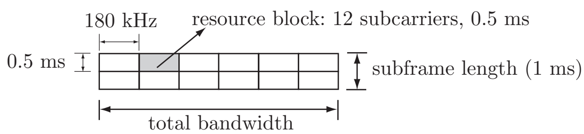

Fig. 1. Resource block grid structure (1 TTI) for a 1.4 MHz bandwidth.

In the time domain, the length of a radio frame is 10 ms, which is divided in 10 subframes, each 1 ms long. Each subframe consists of two 0.5 ms long slots. The Transmission Time Interval (TTI) of LTE is defined to be 1 ms long, so every 1 ms the scheduler must multiplex the users in grid of $N_{\mathrm{RB}}^{\mathrm{DL}} \times 2$ RBs [1]. This also sets 1 ms as the reaction time of the network. Fig. 1 depicts a resource block grid for a 1.4 MHz bandwidth.

The channel coding for the DL-SCH consists of Transport Block (TB) CRC attachment, Code Block (CB) segmentation, a rate 1/3 turbo encoder, rate matching and code block concatenation [8]. Fig. 2 depicts the processing structure for the DL-SCH, naming the bitstream after each process. Data a arrives to the coding unit in form of a maximum of one TB every TTI and a CRC is then attached to it, thus obtaining b. The resulting b bits are then segmented in r c_r CBs. The maximum CB size is 6144 bits, as that is the maximum size allowed by the turbo coder. In case segmentation is performed, an extra CRC is attached to c_r. The bits are then turbo coded and rate-matched, thus obtaining d_r and e_r respectively. Finally, the r CBs are concatenated to obtain the coded TB f.

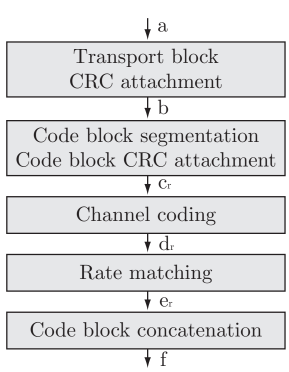

Fig. 2. The LTE DL-SCH channel coding processing structure. The data bits (a) are input and then coded (f).

Depending on channel conditions, different coding schemes and modulations can be used for each RB. Possible modulations for the DL-SCH are 4-QAM, 16-QAM and 64-QAM [9]. While the process is in essence identical to previous technologies such as HSDPA, due to the high data rates involved the structure of the turbo encoding and rate matching is slightly different such as to ease parallelization [10].

The LTE rate matcher will fit the rate 1/3 turbo-coded blocks into the available space assigned by the scheduler in the RB grid via a process of puncturing or repetition, thus obtaining the Effective Code Rate (ECR).

$$\mathrm{ECR} = \frac{c_r}{e_r} \cdot 1024. \tag{1}$$

LTE defines different Modulation and Coding Schemes (MCS) suitable for 15 different steps of the Channel Quality Indicator (CQI) which is feedback by the User Equipment (UE). ECRs between 78 and 948 are specified for LTE [11].

Fig. 3 depicts the rate-matching process for $e_r < d_r$ (ECR increase). The rate matcher plays a crucial role in H-ARQ, as it is performed by controlling the puncturing process depending on the retransmission number.

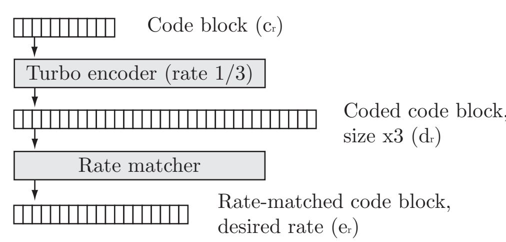

Fig. 3. Rate matching. Bits in the code block are punctured or repeated to achieve de desired ECR.

LTE provides both ARQ and H-ARQ functionalities. The ARQ functionality provides error correction by retransmissions in acknowledged mode at Layer 2, while the H-ARQ functionality ensures delivery between peer entities at Layer 1. In this paper we will focus on H-ARQ with Incremental Redundancy (IR) and how to model its performance in a simple way to use it in system level simulations.

Such models already exist for other technologies, such as the proposal in [4] for HSDPA and can improve the accuracy of current system level simulations such as [5], but so far none has been proposed for LTE.

3. LTE H-ARQ

A transmission scheme based on H-ARQ combines detection and Forward Error Correction (FEC) plus a retransmission of the erroneous packet. LTE additionally uses soft combining, in which a given received packet is combined with the previously received packets and the resulting more powerful FEC code is then decoded [12].

When soft combining the packets received in several H-ARQ retransmissions, basically two combining strategies can be used. These are Chase Combining (CC), where each retransmission is identical to the original transmission, and Incremental Redundancy (IR), where each retransmission consists of new redundancy bits from the channel encoder. In IR, instead of sending simple repeats of the coded data packet, new information is sent in each subsequent transmission of the packet. The decoder then combines all the transmissions and decodes the packet at a lower code rate.

LTE utilizes IR H-ARQ with a 1/3 turbo encoder as FEC code and the TB CRC for error detection. Since in this case the receiver obtains just differently punctured versions of the same turbo-encoded data, each of these retransmission is self-decodable. Such an H-ARQ scheme falls into the category of a type-III Hybrid H-ARQ.

In order for IR to work, the H-ARQ functionality must be able to create appropriate redundancy versions from a given CB and prevent terminal buffer overflow. This is achieved through the rate matcher located after the fixed-rate channel encoder. LTE implements this functionality in a one-step rate matching as opposed to HSDPA, where it is accomplished in a two-step process [13].

Fig. 4 depicts CC in the case when $\mathrm{ECR} > 1024/3$, where the received identical packets are recombined, while Fig. 5 depicts the IR case. The white part in the reconstructed code block represents bits that were punctured from the original CB.

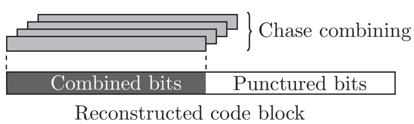

Fig. 4. Chase combining on four received transmissions $\left(\mathrm{ECR} > \frac{1024}{3}\right)$. Punctured bits are still missing after the combining.

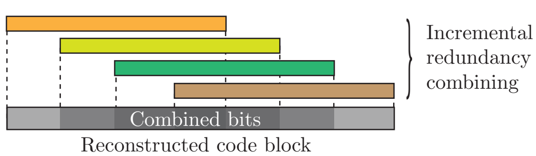

Fig. 5. Incremental redundancy combining on four received transmissions $\left(\mathrm{ECR} > \frac{1024}{3}\right)$. Every retransmission adds extra information bits.

While HSDPA provides both CC and IR H-ARQ, LTE only provides IR. IR can give large performance gains for high channel-coding rates and high modulation orders. For low MCSs, the link-level performance gains with IR are less significant, and there are only a few artificial scenarios in which IR performs worse than CC [14].

H-ARQ transmissions are indexed with the redundancy version $\mathrm{rv}_{\mathrm{idx}}$ parameter, which tells the receiver whether the currently transmitted TB is new (0), or the n-th retransmission, up to a maximum of 3 (1,2 or 3). For a given target TB size G, the rate matcher can produce 4 different punctured versions of the original coded TB, depending on the value of $\mathrm{rv}_{\mathrm{idx}}$ (see Fig. 6). Other parameters that fine tune the rate matching process are Q_m (modulation order), N_{IR} (buffer size at receiver end) and N_l (number of layers used in the channel coding) [8].

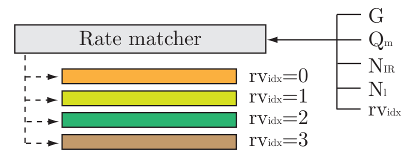

Fig. 6. Through the rate-matching process, up to four different rate-matched versions of a given code block can be produced by varying the $\mathrm{rv}_{\mathrm{idx}}$ parameter.

Link level simulations with H-ARQ showed that the LTE turbo code rate matcher will even in the case of most extreme puncturing ($\mathrm{CQI} = 15$) still introduce 13% of parity bits for $\mathrm{rv}_{\mathrm{idx}} = 0$. For the second, third and fourth transmissions, these ratios change to 83%, 0% and 34% respectively (see Fig. 7).

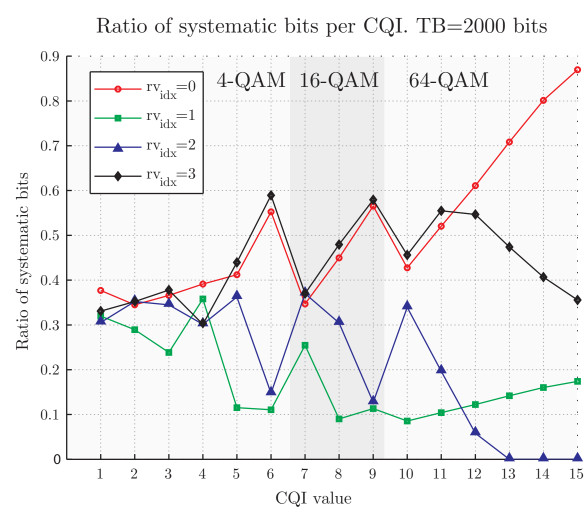

Fig. 7. Ratio of systematic bits in the rate-matched CB for each possible MCS, as defined by the CQI.

When using IR, some degradation can be expected when losing the systematic bits in the original transmission while receiving the parity bits [14]. Including systematic bits in two out of three possible retransmissions aims at reducing this problem. In order to improve the efficiency of H-ARQ, mapping techniques such as the one in [15] have also been used. The scheme used in LTE, depicted in Fig. 8, is based on transmitting systematic and parity bits in the same sent TB.

The rate matching process works by, depending on $\mathrm{rv}_{\mathrm{idx}}$, choosing a starting point in the interleaved CB depicted in Fig. 8 and then choosing G consecutive bits. The $v^{(0)}$ bits are the interleaved systematic bits from the turbo encoder, while $v^{(1)}$ and $v^{(2)}$ the first and second parity bits respectively. This

Fig. 8. Coded bits before the puncturing/repetition in the rate matcher. A contiguous subset of these bits is the output of the rate matcher.

sub-block interleaving process is part of the rate-matching process, and separately spreads the systematic and parity bits over a wider area in the CB.

4. H-ARQ MODELING

For each H-ARQ retransmission that the LTE system can use, an improvement of the Block Error Rate (BLER) is expected. In order to model these improvements, link level simulations have been used [3].

The LTE link level simulations for the H-ARQ evaluation process were performed for a single-user scenario corresponding to the simulation parameters shown in Table 1. All of the 15 MCS defined by the CQI values in the LTE standard [11] have been used. As to have reliable data at BLERs of 10^{-3}, 10,000 subframe-long simulations were performed. MIMO benefits are open for investigation in future work, where we will put an emphasis on investigating different space-time coding schemes (similar to HSDPA [16]), as proposed by the standard.

Parameter	Value
System bandwidth	1.4 MHz
Subcarrier spacing	15 kHz
Cyclic prefix	normal
Channel profile	AWGN
Max. number of retransmissions	3
CQI values	1-15
Simulation length	10,000 subframes

Table 1. Link level simulation parameters.

Simulations were performed with the minimum specified bandwidth for LTE, which is 1.4 MHz. Since the LTE turbo encoder has a maximum CB size of 6144 bits, the channel coding process segments the received TBs when needed. Because of this segmentation, it is not expected that varying the available bandwidth (thus increasing $N_{\mathrm{RB}}^{\mathrm{DL}} = 6$) would change the results presented in this paper.

Fig. 9 shows typical BLER curves generated by the H-ARQ simulations. Each curve represents the BLER of the subframes with a specific $\mathrm{rv}_{\mathrm{idx}}$. The bold curve represents the overall BLER, not taking into account $\mathrm{rv}_{\mathrm{idx}}$. As each retransmission provides the receiver extra information, BLER improves for each additional retransmission. Our proposed H-ARQ model serves at estimating the BLER SNR shift that occurs when H-ARQ is used compared to a transmission that is not using H-ARQ.

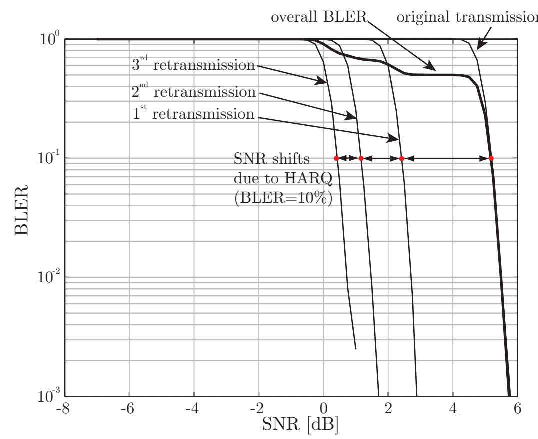

Fig. 9. H-ARQ BLER curves for CQI 7. 16-QAM modulation and 738 ECR.

Simulations were performed for the MCSs corresponding to each CQI value in LTE. Fig. 9 shows only the plot for a CQI of seven, but simulations were performed for all 15 CQI values. From each of these simulations the BLER for each retransmission was evaluated and the shifts between the curves (SNR gain due to H-ARQ) was noted. The shift was defined as the difference between the curve of the n-th retransmission and the original transmission at the BLER $= 10\%$ point. The results of our investigation are illustrated in Fig. 10, which depicts the SNR gain depending on the number of retransmissions ($\mathrm{rv}_{\mathrm{idx}}$), the modulation (4-QAM, 16-QAM or 64-QAM) and the ECR. A linear regression has been performed to fit the simulation results, which is also overlayed onto the plot.

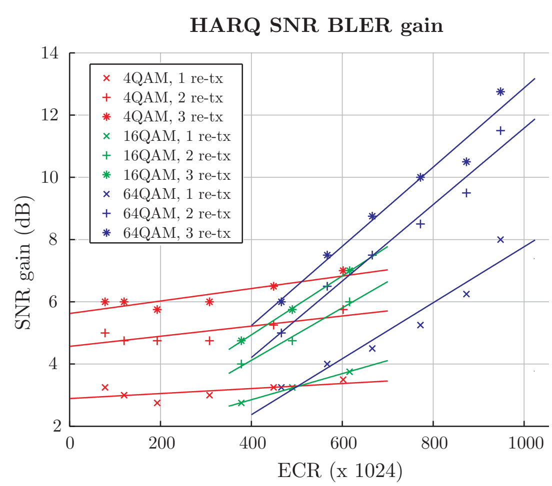

Fig. 10. SNR gain when using H-ARQ and the proposed analytical model.

The SNR gain can thus then be modeled this linear fit, shown in Eq. (2), where $\mathrm{SNR}_{\mathrm{gain}}(\mathrm{rv}_{\mathrm{idx}})$ is expressed in dB. The possible values for μ_{mod} and $\varepsilon_{\mathrm{mod}}$, depending the retransmission index $\mathrm{rv}_{\mathrm{idx}}$ and the modulations specified by the LTE standard can be found in Table 2.

$$\mathrm{SNR}_{\mathrm{gain}}(\mathrm{rv}_{\mathrm{idx}}) = \mu_{\mathrm{mod}}(\mathrm{rv}_{\mathrm{idx}}) \cdot \mathrm{ECR} + \varepsilon_{\mathrm{mod}}(\mathrm{rv}_{\mathrm{idx}}) \quad (2)$$

Modulation	$\mathrm{rv}_{\mathrm{idx}}$	$\mu_{\mathrm{mod}} \cdot 10^{-2}$	$\varepsilon_{\mathrm{mod}}$
4-QAM	1	0.0804	2.89
	2	0.1628	4.57
	3	0.2006	5.62
16-QAM	1	0.0420	1.17
	2	0.8435	0.74
	3	0.9464	1.15
64-QAM	1	0.8996	-1.23
	2	1.2288	-0.71
	3	1.2728	0.15

Table 2. H-ARQ model parameters for 4-QAM, 16-QAM and 64-QAM modulations.

When using our proposed model in a system level simulation, the link level model can then adjust the post-equalization symbol SINR to account for the effect of H-ARQ by means of a simple sum, as shown in Eq. (3), where i denotes the i-th retransmission.

$$\mathrm{SINR}(i) = \mathrm{SINR} + \mathrm{SNR}_{\mathrm{gain}}(i) \quad (3)$$

In system level simulations, the SINR of a transmission without taking H-ARQ into account is calculated by the link measurement model. Afterwards, in order to account for the effect of H-ARQ, a gain of $\mathrm{SNR}_{\mathrm{gain}}(i)$ dBs will be applied to the SINR according to the redundancy version index i and using the correct μ_{mod} and $\varepsilon_{\mathrm{mod}}$ parameters for the given MCS (see Eq. 2), thus obtaining an adjusted SINR value that includes the gain due to H-ARQ retransmissions.

Typical link to system level models utilized for the evaluation of multicarrier systems such as LTE are Exponential Effective SIR Mapping (EESM) and Packet Error Rate (PER) indicator [17]. Such models can be used to obtain the effective SINR of the received TB to which afterwards the H-ARQ gains can then be added.

Although there are already extensions for EESM to deal with H-ARQ [18] showing results for uncoded simulations, our proposed simulation-based model takes into account the whole LTE processing chain, providing a more tailored model for LTE. Details such as the number of new and systematic bits in each retransmission and the performance of the channel coding, which are specific to the LTE system are then taken into account.

Our model shows that, as expected, the highest SNR gains are observed for high modulation orders and ECRs, as IR performs at best in this region [14] (see Fig. 10). Up to a 12.75 dB improvement has been observed for CQI 15 (64-QAM, 948 ECR).

The relative mean square error (MSE) of the estimated SNR gains is shown in Table 3). As it can be seen, relative MSEs show errors below 1% except for the 64-QAM modulation. This high error is due to a mismatch of the model with the actual measured SNR gains for the last two CQI values (873 and 948 ECRs).

Modulation	$\mathrm{rv}_{\mathrm{idx}} = 1$	$\mathrm{rv}_{\mathrm{idx}} = 2$	$\mathrm{rv}_{\mathrm{idx}} = 3$
4-QAM	0.374	0.717	0.805
16-QAM	0.002	0.133	0.016
64-QAM	3.983	6.569	11.273

Table 3. Relative MSE (%) of the proposed LTE H-ARQ model for the different possible modulations and $\mathrm{rv}_{\mathrm{idx}}$.

5. CONCLUSIONS

In this paper, we propose a low-complexity H-ARQ SNR-gain model that is capable of predicting the SNR gain that using the H-ARQ scheme defined for LTE provides. For any of the defined modulation and coding schemes defined for LTE, our model is capable predicting the SNR shift of the block error rate curve that will be obtained for each H-ARQ retransmission.

The proposed model can be used in system level simulations to represent the impact of H-ARQ not only accurately but also with a very low computational complexity. Future work will deal with improving the model for high modulation and coding schemes, frequency selective channels, and MIMO benefits and channels such as the Spatial Channel Model (SCM) [19].

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6. REFERENCES

[1] *Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Physical Layer - General Description*, 3GPP Std. TS 36.201. Release 8, November 2007.

[2] E. Dahlman, S. Parkvall, J. Skold, and P. Beming, *3G Evolution*. Academic Press, July 2007.

[3] C. Mehlführer, M. Wrulich, J. C. Ikuno, D. Bosanska, and M. Rupp, "Simulating the long term evolution physical layer," in *Proc. of the 17th European Signal Processing Conference (EUSIPCO 2009)*, Glasgow, Scotland, Aug. 2009, submitted.

[4] F. Frederiksen and T. Kolding, "Performance and modeling of WCDMA/HSDPA transmission/H-ARQ schemes," *Vehicular Technology Conference, 2002. Proceedings. VTC 2002-Fall. 2002 IEEE 56th*, 2002.

[5] M. Wrulich, W. Weiler, and M.Rupp, "HSDPA performance in a mixed traffic network," in *Proc. IEEE Vehicular Technology Conference (VTC) Spring 2008*, May 2008, pp. 2056–2060.

[6] M. Wrulich, S. Eder, I. Viering, and M. Rupp, "Efficient link-to-system level model for MIMO HSDPA," in *Proc. of the 4th IEEE Broadband Wireless Access Workshop*, 2008.

[7] J. C. Ikuno, M. Wrulich, and M. Rupp, "Simulating long term evolution networks," 2009, to be submitted.

[8] *Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding*, 3GPP Std. TS 36.212. Release 8, March 2008.

[9] *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation*, 3GPP Std. TS 36.211. Release 8, March 2008.

[10] A. Nimbalker, Y. Blankenship, B. Classon, and T. Blankenship, "PHY 40-1 - ARP and QPP interleavers for LTE turbo coding," *Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE*, 31 2008-April 3 2008.

[11] *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures*, 3GPP Std. TS 36.213. Release 8, May 2008.

[12] E. Malkamaki, D. Mathew, and S. Hamalainen, "Performance of hybrid ARQ techniques for WCDMA high data rates," *Vehicular Technology Conference, 2001. VTC 2001 Spring. IEEE VTS 53rd*, 2001.

[13] M. Dottling, J. Michel, and B. Raaf, "Hybrid ARQ and adaptive modulation and coding schemes for high speed downlink packet access," *Personal, Indoor and Mobile Radio Communications, 2002. The 13th IEEE International Symposium on*, Sept. 2002.

[14] P. Frenger, S. Parkvall, and E. Dahlman, "Performance comparison of HARQ with chase combining and incremental redundancy for HSDPA," *Vehicular Technology Conference, 2001. VTC 2001 Fall. IEEE VTS 54th*, 2001.

[15] Panasonic, "Proposal of bit mapping for type-III HARQ," Panasonic, Tech. Rep. input paper TSC+R1#18(01)0031, January 2001.

[16] M. Wrulich and M. Rupp, "Efficient link measurement model for system level simulations of Alamouti encoded MIMO HSDPA transmissions," in *International ITG Workshop on Smart Antennas (WSA)*, Darmstadt, Germany, Feb. 2008.

[17] Y. Blankenship, P. Sartori, B. Classon, V. Desai, and K. Baum, "Link error prediction methods for multicarrier systems," *Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th*, Sept. 2004.

[18] B. Classon, P. Sartori, Y. Blankenship, K. Baum, R. Love, and Y. Sun, "Efficient OFDM-HARQ system evaluation using a recursive EESM link error prediction," *Wireless Communications and Networking Conference, 2006. WCNC 2006. IEEE*, April 2006.

[19] D. Baum, J. Hansen, and J. Salo, "An interim channel model for beyond-G systems: extending the 3GPP spatial channel model (SCM)," *Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st*, May-1 June 2005.