HARQ Power Allocation Schemes for Power-Controlled Systems

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***Abstract*—In this paper different operation modes of HARQ in a power-controlled environment are examined. The investigations compare different strategies to allocate transmission power amongst the HARQ (re-)transmissions based on power efficiency, cell throughput and delay. As a chariot for our endeavor we use system-level simulations of the UMTS enhanced uplink. If the power allocation strategy is restricted to equal power levels of all transmission of one packet, the optimum performance can only be obtained at a relatively high number of average transmissions per packet, i.e. at the expense of increased physical layer delay. A more flexible power allocation strategy, based on reduced power in retransmissions, however, achieves same or superior performance in terms of throughput and transmit power efficiency with notably less delay.**

***Index Terms*—Boosted Mode, De-boosted Mode, HARQ Retransmission power, System-level simulator, Enhanced Uplink.**

I. Introduction

In modern systems fast channel-dependent scheduling is used to exploit multi-user diversity and often combined with Hybrid Automatic Repeat reQuest (HARQ) to obtain implicit link adaptation and robustness. Due to the near-far effect, fast power control is required in many systems (even for packet-oriented services, e.g. in the asynchronous uplink of CDMA systems).

If Hybrid Automatic Repeat reQuest (HARQ) is added to a system with fast power control using the classical power operation point, the received SIR of a failed transmission will in most of the cases be only slightly smaller than the target SIR. If the retransmission is carried out at the same relative transmission power, the combined SIR after retransmission might exceed the required SIR notably, resulting in excess interference and reduced transmit power efficiency. In order to adapt the combined SIR to the target SIR different strategies can be pursued: either the power of all transmissions is adapted equally until an efficient operation mode is achieved or the retransmission can be sent with an appropriate power offset with respect to the initial transmission.

The first strategy is denoted as constant power offset reduction (CPOR). However, equally reducing the power for every transmission may result also in a higher number of retransmissions and therefore delay. The question arises if there is a compromise between throughput maximization and delay minimization. One way to achieve this goal is to allow unequal power offset for each retransmission [1,2]. This approach is called retransmission power adaptation (ReTxPA) in the following. The task of this paper is to investigate and compare both ideas and to examine appropriate operation points in a realistic system-level simulation.

In the following section a brief description of the system-level simulator and its assumptions are given. In section 3 the different schemes and their main ideas are described in more detail while in section 4 simulation results are presented. Finally in section 5 some conclusions are drawn.

II. Simulation Assumptions

In this section the system-level simulator and the parameters used in this simulation campaign are described. As a target system to apply these HARQ retransmission schemes, the UMTS enhanced uplink is used but the ideas presented here may also be applied to 4G systems. The cell layout uses a hexagonal grid with 3-sector sites and 27 cells with a wrap-around technique and an antenna pattern given in [3]. The site to site distance is assumed to be 2800 m. Every cell is simulated with two-antenna Rx diversity. For the simulations presented here, a full buffer traffic model is used, however, similar results are obtained for packet data models. The frame and scheduling duration is set to 10 ms. A possible 2 ms frame length is not taken into account here but the results should not be much different according to [4]. The base station applies a time and rate scheduling with a Max C/I or Round Robin scheduler. The scheduling decision is based on an interference margin which is represented by the Rise over Thermal (RoT) or noise rise value in the UMTS context [5]. The maximum active set size is three and mobiles which are in Soft HandOver (SHO) are permitted to transmit at a maximum data rate of 32 kbps. The used HARQ scheme is Chase Combining with 3-channel Stop And Wait (SAW) protocol and a maximum number of three retransmissions according to [3]. The propagation channel uses the Vehicular A (VA) power delay profile with 30 kmph for 2 GHz carrier frequency. The delay between a transmission request of the user terminal and the actual grant of resources from the network is set to 60 ms. Every simulation consists of three uncorrelated drops of users in the network, each drop containing a simulation time of 40 seconds.

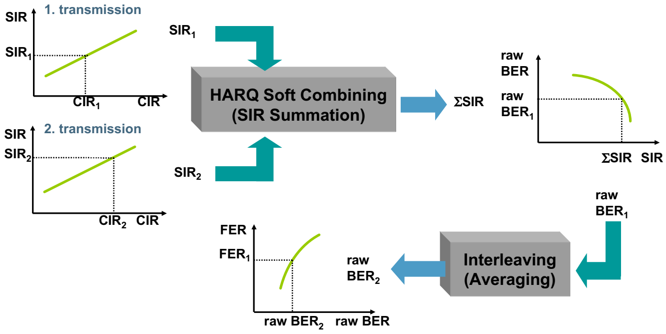

Fig. 1. Schematic of the actual value interface

The whole system is based on an actual value interface depicted in Fig. 1 and derived from [6]. The actual value interface computes the CIR on slot basis and converts it to a SIR based on link level regression curves. For Chase Combining, it also calculates the effective SIR after soft combining and maps it to a raw BER. After averaging the raw BER per slot over the interleaving length which is one frame, it is mapped to a BLER. The transport formats used within the simulator range from 8 kbps up to 1280 kbps.

III. Power Offset HARQ schemes

Obviously, the most efficient way to transmit data is to send it with the exact amount of power needed for an optimal detection. Unfortunately this power level cannot be obtained exactly in a cellular mobile communication system and explicit and/or implicit link adaptation is used, e.g. due to power control or HARQ. For the link adaptation two basic requirements need to be considered:

1. Minimize user delay
2. Maximize cell throughput

In order to minimize the delay of a scheduled user, re-transmissions should be avoided. A simple way to achieve this goal is to boost the power that no or little retransmissions are necessary. In order to keep it simple we may also transmit the few retransmissions with the same (high) power offset. This variation of the CPOR scheme is referred to as boosted mode.
However, the constraint of very low BLER at the initial transmission results in low power efficiency and high noise rise consisting of two parts:

1. Noise rise due to higher power offset in case of successful first transmission.
2. Noise rise due to retransmission

The problem with the second point can be seen in the first part of the schematic depicted in Fig. 2. In this example we are very close to the power level needed. The necessary retransmission in boosted mode wastes a lot of energy resulting in interference and noise rise. Due to this the probability of a second retransmission is close to zero. Therefore an optimum for the boosted mode in terms of throughput can be found around 5-20 % BLER after first transmission. This results in an average number of needed transmissions for one frame of around 1.1. In this paper we define this boosted mode according to the average number of necessary transmissions between 1 and 1.5 for one block.

In order to allow better throughput the power offset can be reduced/de-boosted significantly. In theory, if infinite retransmissions (and therefore delay) are permitted, an infinite number of mobiles can be scheduled, and if the signaling overhead is neglected the best throughput can be achieved if the power per user is minimal (>0). In this case we transmit as many transmissions as needed to reach the necessary power level and the additional noise rise is negligible. These theoretical considerations can be adapted to a practicable system based on a finite number of transmissions. In [3] and [5] the proposal was made for a CPOR with an power offset resulting in a BLER after the first retransmission of about 1 % which is called de-boosted mode in this investigation. Different from [3] we define de-boosted mode in terms of average number of needed transmissions for one data frame which should be between 1.5 and 2.5. In [7,8] and others it is also called nominal mode and it is depicted in the second part of Fig. 2. In order to spin this idea a little bit further we will also add a super de-boosted mode with an average number of transmissions between 2.5 and 3.5. Actually the de-boosted mode has the same optimization problem like the boosted mode. The difference is merely that the transmission power is optimized such that exactly two transmissions are needed nearly every time. Therefore the noise rise consists again of two parts:

1. The sum of the power of the first transmission and retransmission and its resulting noise rise
2. Noise rise due to a possible third transmission

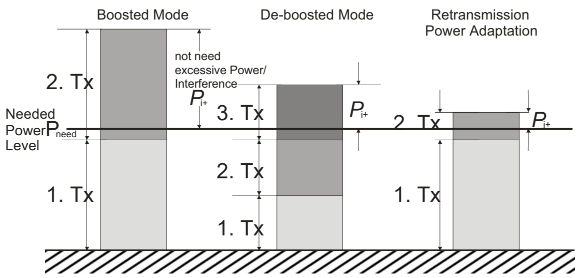

Fig. 2. Boosted, De-boosted and ReTxPA scheme-principle

Because the (re-)transmission powers are smaller, also the noise rise margins are much smaller compared to the boosted mode and we may receive a significant gain after optimizing. The super de-boosted mode works in the same way like described before but its gain compared to the boosted mode may be even larger.

While the boosted mode has the benefit of short delay, the de-boosted mode provides higher power efficiency. A straight forward idea is to combine the advantages of both variants, be designing an HARQ power adaptation scheme which combines both advantages, i.e. operates under the constrains of around 10% BLER after the initial transmission and around 1% BLER after the second transmission. Therefore the first transmission is transmitted with high power (some sort of boosted mode) while the first retransmission is transmitted using a much smaller power level, just enough to receive the data correctly. In case of an error after second transmission the second retransmission can also be transmitted with low power too. In order to avoid any problems with higher layer retransmissions the last retransmission should be transmitted with the same high power level as the first transmission. Due to the low probability of this last retransmission, the overall penalty due to this high-power transmission is negligible. This scheme is called retransmission power adaptation (ReTxPA) in the following and it was proposed in [1,2] and is depicted in the third part of Fig. 2.

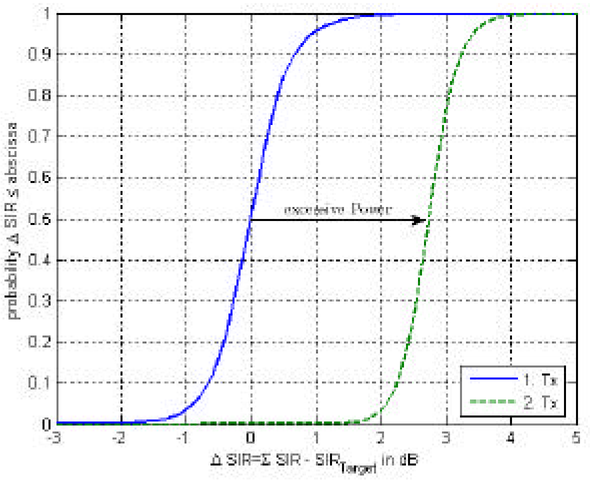

Fig. 3. Cumulative SIR distribution over the difference SIR after soft combining for boosted mode

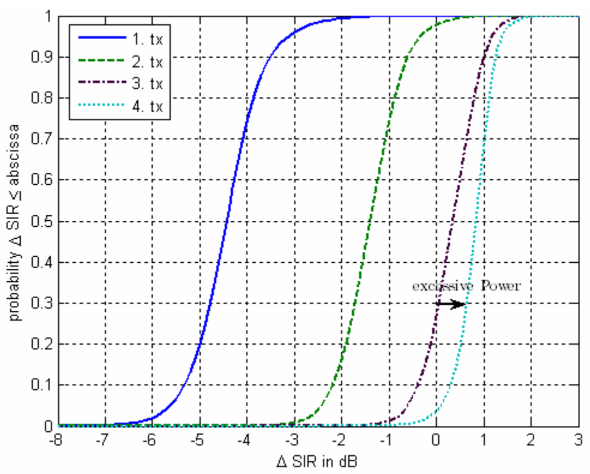

Fig. 4. Cumulative SIR distribution over the difference SIR after soft combining for super de-boosted mode

In the optimal case the scheduler is aware of the reduced power in retransmissions and exploits this knowledge proactively in the resource allocation process. However, also without such knowledge, the overall number of scheduled users will increase based on reduced average noise rise experienced.

While power offset values of the boosted, de-boosted mode are a one dimensional optimizing problem, this is not the case for retransmission power reduction. However, in practice, it is most important to obtain the optimum power settings of the first two transmissions, since these will foster the majority of gain. In the sequel the power offsets were investigated under the constraint to meet a BLER between 1 % and 2 % after the first retransmission. The effects can be seen best in the cumulative distribution functions (CDF) of the difference between the SIR after soft combining from the target SIR, denoted as ΔSIR and depicted in Fig. 3, Fig. 4 and Fig. 5.

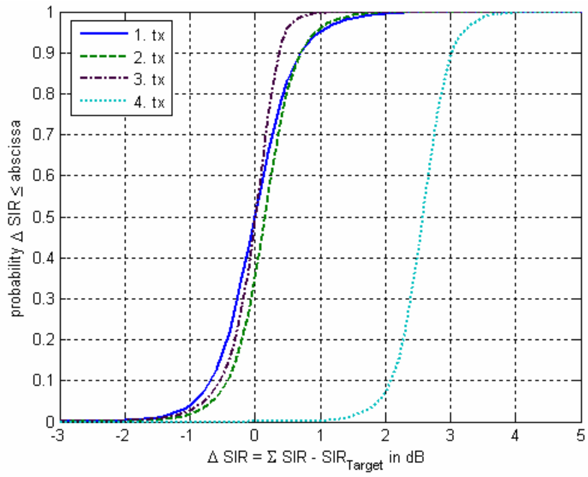

Fig. 5. Cumulative SIR distribution over the difference SIR after soft combining for retransmission power adaptation

These CDFs can be used for a first estimate of the power offset. Fig. 3 shows the first two transmissions of a boosted mode and Fig. 4 the transmissions of the super de-boosted mode. At 0 dB the received SIR equals the target SIR and most mobiles which yield an erroneous transmission do not reach this target SIR. These retransmitting mobiles in boosted mode yield a ΔSIR thanks to HARQ which results in an excessive waste of power shown in Fig. 3. The super de-boosted mode is quite similar but only after three transmissions the 0 dB line is crossed for a significant amount of mobiles and the excessive power needed between third and fourth transmission is rather small. Fig. 5 represents the CDF of a system with ReTxPA. The power is reduced in a way that nearly no excessive power is needed which results in a steeper and slightly shifted slope compared to the one of the first transmission. The power offset for the second transmission of about -8dB with respect to the initial transmission has proven itself to be useful according to [2] and the simulations presented in this paper.

In order to allow different QoS profiles the transmission curves can be shifted accordingly, so that a certain given BLER after a certain transmission is reached like in our case 1-2 % after second transmission. Table 1 summarizes the expected properties of the different schemes.

One topic not covered in this paper is the additional costs of each scheme in terms of signaling. It is obvious that each system which needs per average more retransmissions needs also a higher number of HARQ-related signaling (e.g. Ack/Nak feedback). For ReTxPA the attenuation values with respect to the retransmission number have only to be signaled with low frequency (semi-static), since the optimum power offset is relatively robust against changes in mobility. Note, that this signaling actually would allow to implement all power allocation strategies discussed in this paper, i.e., the ReTxPA scheme can easily be transformed to boosted, de-boosted or super de-boosted mode.

TABLE I
EXPECTED PROPERTIES OF THE INVESTIGATED MODES

Mode	Delay	Throughput	Costs
Boosted	minimal	medium	normal
De-boosted	medium	good	double Ack/Nak
Super de-boosted	high	very good	triple Ack/Nak
ReTxPA	low	good	close to normal in signaling.

IV. SIMULATION RESULTS

In this section simulation results are presented to evaluate the performance of the different HARQ power allocation schemes. As stated before we use a Vehicular A (VA) channel with 30 kmph. The average number of mobiles within a cell is fixed to 10. We use two schedulers the Max C/I and the Round Robin, therefore every other scheduler like Proportional Fair should yield results in between. In Fig. 6 the throughput versus the average number of transmissions for a RoT of approximately 4.7 dB is depicted.

Looking first at the CPOR scheme we witness three maxima which can be denoted as optimal working points for the boosted, de-boosted and super de-boosted mode. These three maxima are always close over an integer of transmissions where the cost of an additional retransmission and noise rise due to the previous transmissions are minimal. The main statistical properties like noise rise and its standard deviation or average number of scheduled mobile or necessary transmissions per block can be found in table 2 for Max C/I and table 3 for Round Robin scheduler. While the gain of approx. 10 % compared to the boosted mode was expected, it is interesting to see that actually the super de-boosted mode performs slightly worse with the Max C/I scheduler. A reason for this is the increased number of users scheduled in the super de-boosted mode (45% compared to 32% in de-boosted mode). This results in reduced gain due to channel-dependent scheduling, since on average also more users with non-favorable channel conditions are served. Therefore it degrades with about 2 % compared to the de-boosted one. The Round Robin scheduler performs about 19-25 % worse than the Max C/I. In this case the super de-boosted mode outperforms the boosted and de-boosted mode as expected (since no multi-user diversity is exploited anyway). It should also be noted that the RoT standard deviation reduces from boosted to super de-boosted mode due to the increasing number of scheduled mobiles.

In Fig. 6 and Fig. 7 the ReTxPA scheme is only presented by its operational point due to the 1-2 % BLER constraint after first re-transmission. The average number of transmissions is roughly the same for different BLER after first transmission. It outperforms all the schemes with constant power offset with a Max C/I scheduler and performs similar to the super de-boosted mode with Round Robin. It gains about 11 % compared to boosted mode and about 2 % compared to the de-boosted one using a Max C/I. For the Round Robin scheduler compared to boosted mode the gain is slightly higher (≈ 14 %).

TABLE II
STAT. RESULTS FOR MAX C/I, VA, ROT=4.7 dB

	Boosted	De-Boosted	Super De-Boosted	ReTxPA
Cell Throughput in kbps	1198.0	1312.7	1282.7	1337.3
Noise Rise (RoT)	4.7 dB	4.7 dB	4.7 dB	4.7 dB
Noise Rise std	1.5 dB	0.2 dB	-0.5 dB	1.6 dB
BLER after 1^{st} Tx	11.3 %	99.4 %	98.9 %	22.0 %
BLER after 2^{nd}Tx	$<10^{-5}$	15.3 %	94.6 %	1.65 %
BLER after 3^{rd}Tx	0	$2 \cdot 10^{-4}$	15.6 %	0.25 %
BLER after 4^{th}Tx	0	0	1.63 %	$<10^{-5}$
Avg # of Tx.	1.11	2.21	3.08	1.24
Avg sched. mobiles	18.8 %	32.1 %	44.6 %	22.5 %

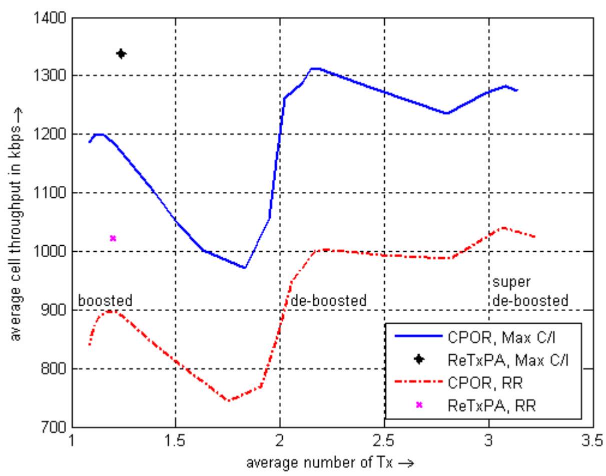

Fig. 6. Throughput versus average number of transmissions for RoT=4.7dB, VA 30 kmph

Another performance measurement is the average transmission power per bit depicted with respect to the average number of transmissions in Fig. 7. The average transmission power per bit is normalized to the control channel power per bit. Therefore it is merely independent of the fading effects initiated by the mobile transmission channel or the distance and allows a fair comparison. Due to this the CPOR curves for Round Robin and Max C/I are quite similar.

It is important to note, that ReTxPA achieves almost the power efficiency of the de-boosted mode and at the same time reduces the physical layer delay by 45 % (average number of transmission is reduced from 2.2 to 1.2).

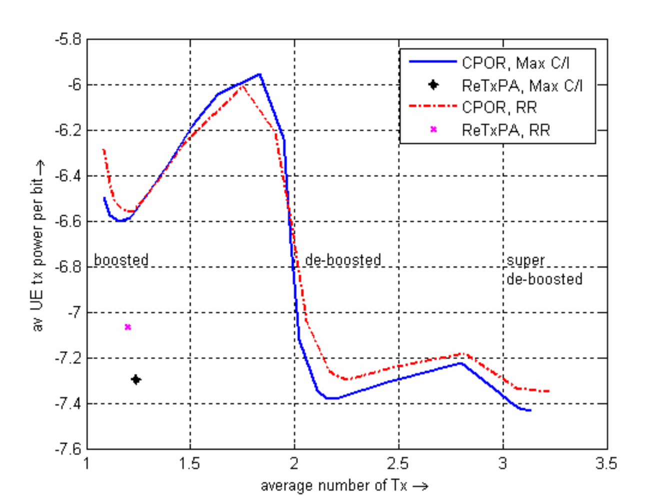

Fig. 7. Average UE transmission power per bit with respect to the average number of transmission for VA with 30 kmph

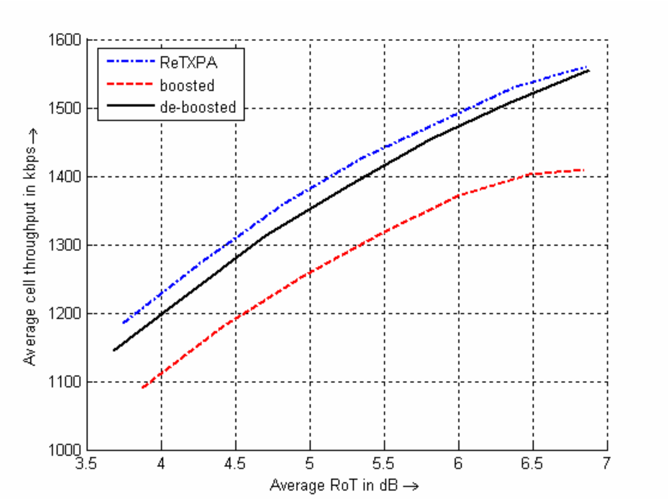

Fig. 8. Cell throughput versus average RoT for the Max C/I scheduler and a Vehicular A channel with 30kmph

In Fig. 8 the average cell throughput for the boosted, de-boosted, and the retransmission power adaptation strategy are depicted for varying average interference in the network (average RoT). The super de-boosted mode is not shown because it did not show a gain compared to de-boosted mode for Max C/I scheduler according to Fig. 6. The average RoT gain of the ReTxPA scheme compared to the de-boosted mode is about 0.2 dB and with respect to boosted mode it is about 0.9 dB. At higher average RoT values the boosted mode goes faster into saturation compared to de-boosted mode or ReTxPA.

V. Conclusion

In this paper we investigated HARQ power allocation schemes in power-controlled systems. Simulation results for Max C/I and Round Robin scheduler using a VA channel with 30 kmph were presented and analyzed. Due to excessive interference the boosted mode is inferior in terms of throughput and transmit power efficiency. The de-boosted mode provides an alternative to the boosted mode by reducing the power offset equally for every transmission. This results in a much better throughput with the disadvantage of additional delay due to an average number of 2.2 transmissions for each block. Reducing the power of the retransmissions compared to the initial transmission can be seen as the perfect compromise: it provides similar cell throughput and transmit power efficiency but introduces around 45 % less delay due to HARQ retransmissions.

TABLE III
Stat. Results for Round Robin, VA, RoT=4.7 dB

	Boosted	De-Boosted	Super De-Boosted	ReTxPA
Cell Throughput in kbps	897.0	1002.7	1039.9	1022.3
Noise Rise (RoT)	4.8 dB	4.7 dB	4.6 dB	4.7 dB
Noise Rise std	2 dB	1.1 dB	0.6 dB	1.3 dB
BLER after 1st Tx	17.1 %	98.9 %	99.1 %	17.1 %
BLER after 2nd Tx	$3 \cdot 10^{-5}$	26.2 %	92.1 %	1.96 %
BLER after 3rd Tx	0	0.29 %	19.3 %	0.56 %
BLER after 4th Tx	0	$<10^{-5}$	1.00 %	$<10^{-5}$
Avg # of Tx.	1.17	2.25	3.06	1.20
Avg sched. mobiles	24.6 %	50.8 %	68.5 %	30.4 %

VI. Acknowledgement

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