Optimization of link adaptation and HARQ schemes for multicast in high speed cellular networks

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***Abstract*—This paper targets multicast transmission where the same data is destined to many users simultaneously. Although multicast allows bandwidth saving, it prevents a precise link adaptation over radio links. Indeed, users are subject to the same bitrate despite their different and variable radio conditions. Neither operators nor 3GPP standard offer solutions to support link adaptation in a multicast scenario. In this context, we propose different solutions. We compare conservative and aggressive schemes by computing the resulting throughput performance. For this purpose, we propose a model to compute the average number of retransmissions. We also study the mapping between the reported SNR and the packet sizes in HSDPA systems. We show that the existing mapping offers the best performance for unicast but cuts down the throughput in a multicast scenario. Then, we propose a convenient mapping for multicast, namely shifted mapping. Despite the better precision of this solution, the resulting gain remains marginal.**

I. INTRODUCTION

The progress of cellular networks like High Speed Downlink Packet Access (HSDPA) [1] is enabling the delivery of very demanding services in terms of network resource. At present, these services are delivered using unicast. As a separate connection is maintained for each recipient, the system does not scale well as the number of terminals increases. Because spectrum is a limited and expensive resource, multicast seems a promising alternative because data is sent only once if multiple users want to receive the same data on the same channel [2]. However, multicast imposes several constraints to the link adaptation process, as a user-specific adaptation of the radio parameters (e.g., to track fast fading) can not be used. In fact, given several users, each of them having a different instantaneous Signal to Noise Ratio (SNR), it is difficult to find a bitrate that fits all the users simultaneously. We propose to compare different strategies for bitrate allocation may be foreseen, namely conservative and aggressive schemes. The former scheme is constrained by the lowest SNR, error rates are then set to the minimum but data blocks are smaller. Conversely, although the aggressive scheme supports larger packets, it increases both the BLock Error Rate (BLER) values and the average number of transmissions, affecting the system throughput. Multimedia Broadcast/Multicast Service (MBMS) [3] has been standardized for the support of multicast over high speed cellular networks. However, the current MBMS version supports neither retransmissions nor feedbacks needed for link adaptation. Our work considers the performance of these mechanisms in a multicast context.

Indeed, packet errors may be frequent if the multicast bitrate exceeds some users' capacity. Different solutions are possible to counter the resulting packet loss. 3GPP proposes the option of Forward Error Correction (FEC) coding [4]. FEC protects data by adding some redundancy at the expense of the effective data-rate. Automatic Repeat Request (ARQ) mechanism represents an alternative to FEC or an enhancement solution that may be combined with FEC. ARQ addresses erroneous data reception using packet retransmission. Although the standard specifies no methods for the management of retransmissions in multicast, different algorithms may be used for this purpose. The simplest retransmission scheme is to retransmit to the whole cluster when, at a Transmission Time Interval (TTI), a NACK is sent from a member of this cluster to the Node B. However, this scheme is pessimistic as a terminal that sends a NACK at a TTI may have correctly received the same packet during a previous TTI. In other words, useless retransmissions may be often triggered. We qualify this scheme as memoryless. Alternately, ARQ can be memory-based. In this case, a retransmission happens only if at least one user has not received a packet during successive transmissions of the same packet. This paper offers a model for the comparison of the aforementioned retransmission mechanisms with the focus on the resulting throughput performance.

In order to improve the retransmission mechanisms' performance in an HSDPA context, it is interesting to take advantage from Hybrid ARQ (HARQ). In fact, with HARQ, a failed transmission is not dumped, instead it is stored to be combined with the next transmission(s) of the same packet. Chase combining (CC) is among the possible HARQ algorithms where transfer reattempts concern identical copies of the freshly sent packet. Hence we evaluate the impact of CC on both memoryless and memory-based schemes.

Adaptive Modulation and Coding (AMC) is among the main techniques that govern link adaptation performance in HSDPA. AMC depends on the transmitted Transport Block Size (TBS), which in turn is signaled via the Channel Quality Indicator (CQI). The CQI values are calculated with the help of SNRs at each terminal and fed back to the Node B. Hence, an appropriate CQI estimation is necessary to transmit packets with TBSs that maximize the system throughput. Current work focus on SNR to CQI mapping in the framework of a unicast transmission. However, this mapping may increase packet loss for multicast transmissions, reducing the throughput performance because of retransmissions. To the best of our knowledge, the multicast context has never been addressed to deal with these issues. Hence, our work targets the enhancement of SNR to CQI mapping for multicast.

This paper is organized as follows. In Section II, we compute the average number of retransmissions using the memoryless and the memory-based approaches. Section III studies SNR to CQI mapping issues in an HSDPA context and proposes adaptations to multicast, namely the SNR-shifted strategy. In the same context, we compare different link adaptation methods including conservative and aggressive strategies. Conclusions are drawn in Section IV.

II. Computation for different retransmission schemes

We consider a Node B that transmits the same service to N terminals. Each terminal i has a different instantaneous SNR value according to its current channel quality. Let $p_{n,i}$ be the probability to lose the n^{th} transmission of the packet destined to user i and $\gamma_{n,i}$ the SNR of user i at the n^{th} transmission.

A. Average number of transmissions using the memoryless approach

In the case of a memoryless scheme, the retransmission of a packet is independent of previous transmission(s) of the same packet. A transmission is considered successful if and only if, at one transmission, all members of the multicast group send an ACK. Then, the probability that transmission n fails can be calculated as shown below

$$p_n = 1 - \prod_{i=1}^{N} (1 - p_{n,i}). \qquad (1)$$

Despite the simplicity of this scheme it leads to a high average number of transmissions. We denote this number as τ_N. It is computed as follows

$$\tau_N = \sum_{n=1}^{\infty} \left(n(1 - p_n) \prod_{m=1}^{n-1} p_m \right). \qquad (2)$$

Combining (1) and (2), we obtain

$$\tau_N = \sum_{n=1}^{\infty} \left(n \prod_{i=1}^{N} (1 - p_{n,i}) \prod_{m=1}^{n-1} (1 - \prod_{i=1}^{N} (1 - p_{m,i})) \right). \qquad (3)$$

Considering a stationary channel for each user, we assume the SNR to be constant during retransmissions. Thus, the BLER is fixed over time and $p_{n,i} = p_i$. In the particular case of equivalent users, we have $p_{n,i} = p$ and (3) becomes

$$\tau_N = \sum_{n=1}^{\infty} \left[n(1-p)^N \left(1 - (1-p)^N\right)^{n-1} \right] \qquad (4)$$

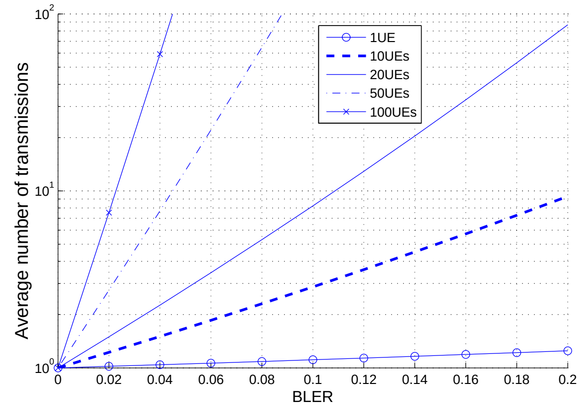

Fig. 1. Average number of transmissions with the memoryless approach

which can be simplified to

$$\tau_N = \frac{1}{(1-p)^N}. \qquad (5)$$

For N=1, we can find the conventional result that gives the average number of transmissions for a single user with a constant-BLER channel:

$$\tau_1 = \frac{1}{1-p}. \qquad (6)$$

Fig. 1 represents the average number of transmissions versus the BLER considering different numbers of User Equipments (UEs). We can see that for a BLER of 10%, only 1.1 transmission is needed on average for one user versus about 3 transmissions for 10 users. In order to have the same average number of transmissions, a BLER of 10% for N=1 corresponds to a BLER of 1%, 0.5% and 0.2% for N=10, N=20 and N=50, respectively. Indeed, BLER requirements become more strigent for a higher number of users.

B. Average number of transmissions with the memory-based approach

We introduce a memory-based approach where a retransmission is required if at least one user has not correctly received a packet during all the previous transmissions of that packet. Let T_i be the number of transmissions to user i before success and T the number of transmissions to the whole group before success. Hence, the cumulative distribution function (CDF) of T is given by

$$\mathbb{P}(T \leq n) = \prod_{i=1}^{N} \mathbb{P}(T_i \leq n) \qquad (7)$$

which can be rewritten as follows

$$\mathbb{P}(T \leq n) = \prod_{i=1}^{N} \left(1 - \prod_{k=1}^{n} p_{k,i} \right). \qquad (8)$$

The average number of transmissions before success is given by

$$\tau_N = \sum_{n=0}^{\infty} 1 - \mathbb{P}(T \leq n). \qquad (9)$$

Substituting (8) in (9), we obtain

$$\tau_N = \sum_{n=0}^{\infty} \left[1 - \prod_{i=1}^{N} \left(1 - \prod_{k=1}^{n} p_{k,i} \right) \right]. \quad (10)$$

In the particular case of equivalent users with a stationary channel, we have $p_{n,i} = p$ and from (10), we obtain that

$$\tau_N = \sum_{n=0}^{\infty} \left[1 - (1 - p^n)^N \right]. \quad (11)$$

For N=1, we can easily find the conventional result in (6).

Fig. 2 represents the resulting average number of transmissions versus the BLER considering different numbers of users. Of course, the average number of retransmissions is cut down compared to the memoryless approach. For instance, with a BLER of 10% and N=20 users, the memoryless approach leads to about 8 retransmissions while the memory-based approach leads to about 2.1 retransmissions.

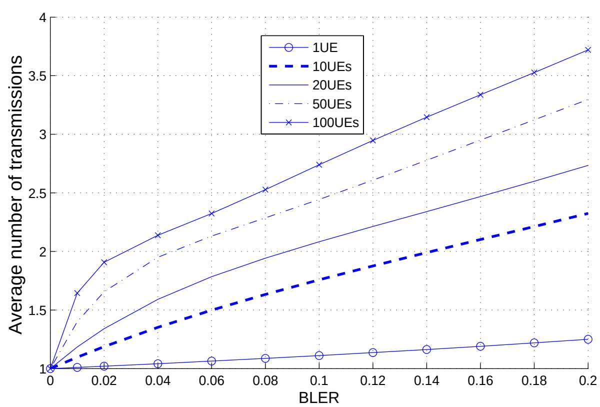

Fig. 2. Average number of transmissions with the memory-based approach

C. Throughput computation

The average throughput depends on the average number of retransmissions and then on both of the retransmission strategy and N. Let R_{mcast} be the multicast throughput, it is given by

$$R_{mcast} = \frac{\beta(bits)}{D_{TTI}(sec)\tau_N} \quad (12)$$

where β is the TBS value and D_{TTI} the TTI duration.

III. Study of an HSDPA system

HSDPA allows to improve the performance of the retransmission schemes through the use of HARQ. For the sake of simplicity, we focus on Chase combining (CC) that retransmits an identical copy of the erroneous packet. When Chase combining is used, we denote as $\gamma_{n,i}^c$ the cumulated SNR at transmission n to UE i. The value of $\gamma_{n,i}^c$ increases at each retransmission and is formulated as follows

$$\gamma_{n,i}^c(dB) = 10.\log_{10}\Big(\sum_{k=1}^{n} 10^{\frac{\gamma_{k,i}}{10}}\Big) \quad (13)$$

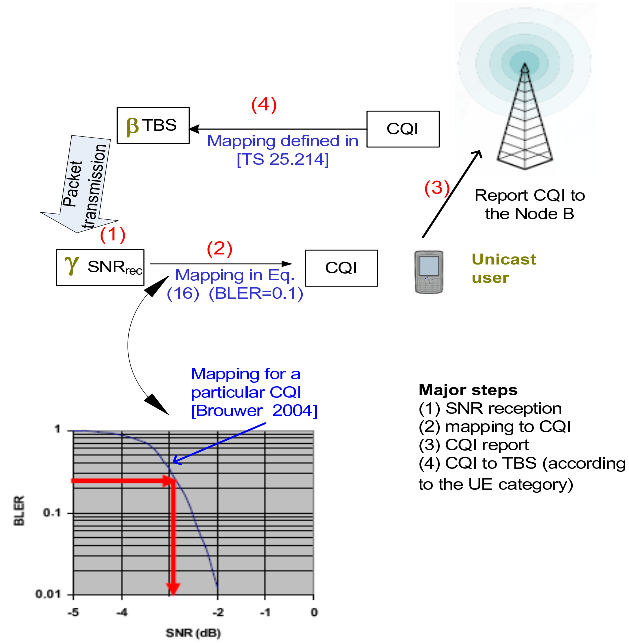

Fig. 3. Radio metrics in HSDPA

In the case of a stationary channel, $\gamma_{k,i}$=γ_i ($k = 1..n$). Hence, equation (13) becomes

$$\gamma_{n,i}^c(dB) = 10.\log_{10}(n) + \gamma_i. \quad (14)$$

HSDPA specification [1] introduces a new metric called Channel Quality Indicator (CQI). As it is shown in Fig. 3, the TBS of the transmitted packet is adjusted according to the signaled CQI by means of a mapping as defined in 3GPP standard [5]. Valid CQI values range from 1 to 30 and the higher the CQI, the better the link quality. The CQI is in turn deduced from the SNR value. Conventional link adaptation is based on BLER vs SNR curves. In HSDPA, the probability a block is received correctly depends on the SNR, the CQI and the receiver implementation [6]. Each CQI has a specific relation between SNR and BLER. Study [7] provides the relationship between BLER, CQI and SNR as follows

$$p_{n,i} = \left(\frac{1}{10^{\frac{2(\gamma_{n,i} - 1.03CQI + 17.3)}{\sqrt{3} - \log_{10}(CQI)}} + 1} \right)^{\frac{1}{0.7}}. \quad (15)$$

Although [7] proved the near perfect match between (15) and HSDPA link-level simulations, there is however no closed form solution to express the CQI as a function of BLER and SNR. The TBS selection in HSDPA is performed for a BLER lower than 10% [5]. For this BLER value, the relation between CQI and SNR is approximated through a linear function with a root mean squared error lower than 0.05 dB [7]. This function is expressed as follows:

$$CQI = \begin{cases} 0 & \text{if } SNR \le -16 \\ \left\lfloor \frac{SNR}{1.02} + 16.62 \right\rfloor & \text{if } -16 < SNR < 14 \\ 30 & \text{if } 14 \le SNR \end{cases} \quad (16)$$

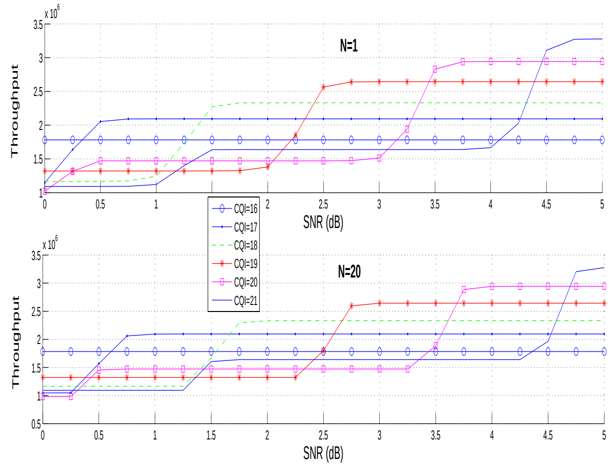

Fig. 4. Throughput vs the SNR for CQI 16-21 (1/20 UE(s), WITH CC)

Using (16) and TBSs in [5], we draw the throughput vs the SNR for different CQI values with Chase combining. Fig. 4 shows the resulting performance for CQI values ranging from 16 to 21 and considering 1/20 user(s).

We aim at verifying whether (16) gives a good match between SNR and CQI in the case of a single user and also multicast for N users (e.g. N=20). Looking at Fig. 4 for N=1, we verify on the example of CQI=20 that the highest throughput is delimited by the SNR range [3.4,4.4]. This range corresponds to the set of solutions of (16) for CQI=20. We can verify that in most of the CQI values, the best performance is delimited by the SNR ranges given by (16).

However, for 20 users, the existing SNR to CQI mapping does not always offer the best performance. For instance, according to (16), an SNR of 0.5 is mapped to CQI=17. It can be verified in the plots for N=1, that this CQI value offers the highest performance. However, when switching to 20 users, the best CQI becomes equal to 16. This is due to the higher average number of transmissions obtained with CQI=17. Similarly, it can be verified on Fig. 4 that an SNR of 1.5 dB matches a CQI equal to 18 for 1 UE but a CQI equal to 17 for 20 UEs. Indeed, when the number of users increases, it is better to consider a more conservative SNR to CQI mapping scheme to increase the throughput performance. This is addressed in next section.

A. *"SNR-shifted" strategy in HSDPA*

In this section, we propose an adaptation to multicast of the existing SNR to CQI mapping scheme. The idea is to compute the reduction of the required BLER when switching from unicast to multicast such that the average number of transmissions remains the same. Then the corresponding SNR loss is translated as a shift that should be introduced (16). In this context, we introduce the *SNR-shifted* strategy. The so-called solution maps SNRs to lower CQI (equivalently TBS) values compared to (16). As such, the "SNR-shifted" strategy

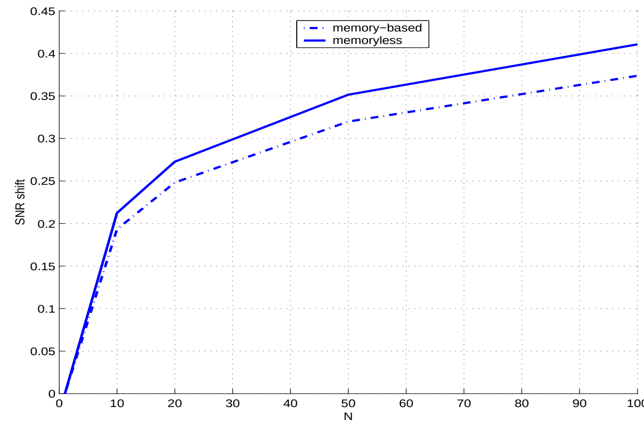

Fig. 5. Required SNR shift (target BLER≤10%)

is given by

$$CQI = \begin{cases} 0 & \text{if } SNR \leq -16 \\ \lfloor \frac{SNR-\alpha}{1.02} + 16.62 \rfloor & \text{if } -16 < SNR < 14 \\ 30 & \text{if } 14 \leq SNR \end{cases} \quad (17)$$

where α is the shift value. We recall that in HSDPA, the TBS selection targets a 1 dB step size in SNR in AWGN channel conditions for a BLER of 10% [5]. This means that the CQI is incremented by one when the SNR increases by a value around one. Thus, the SNR shift has to be lower than one. It is also noteworthy that the shift value depends on several parameters. These include the HARQ retransmission strategy, the number of multicast users and the target BLER. Here are the major steps for the determination of the SNR shift:

1) Fix the HARQ retransmission strategy and the target BLER for a single user,
2) For this BLER value (e.g. 10%), we deduce the corresponding BLER for N ($N > 1$) to obtain the same average number of retransmissions,
3) The BLER shift is then translated to an SNR shift.

Fig. 5 shows the required SNR shift versus N for different retransmission strategies. We see that the SNR loss is higher for the memoryless retransmission scheme. Considering 20 users, we see that the memory-based scheme requires a shift of 0.24 dB while the memoryless scheme needs a shift 0.27 dB. Also the shift increases with N, it reaches 0.41 for 100 terminals using the memoryless approach.

Fig. 6 shows the throughput performance for different scenarios with CC. We see that the shifted SNR to CQI mapping offers a higher or an equal performance compared to the mapping in (16). The equality is obtained for SNR values that belong to the intersection of the shifted SNR range given by (17) and the SNR ranges for unicast (cf. (16)). For instance, SNR= 3 corresponds to CQI=19 for both the unicast and the shifted SNR to CQI mapping (cf. Fig. 4). Otherwise, the shifted values offer higher performance. This is the case of SNR=0.5 dB for example. Note that, in Fig. 6, the throughput stabilizes for SNRs that are higher than a value around 6 dB.

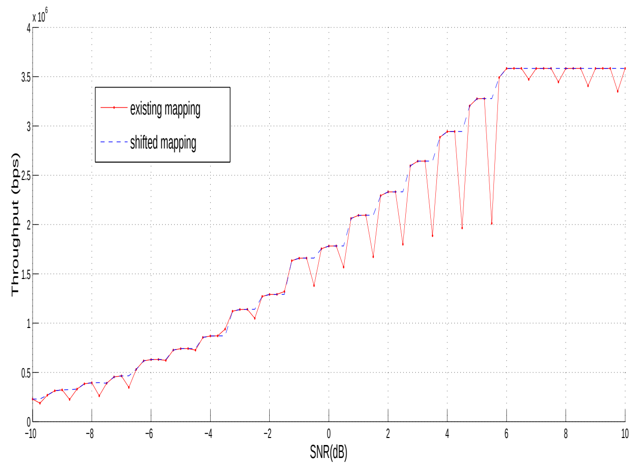

Fig. 6. Throughput of the existing SNR to CQI mapping vs the proposed shifted mapping (20 UEs)

In fact, transport block sizes become constant from this range [5].

B. Link adaptation strategies

Users of the same group might have different SNRs. In multicast, the Node B has to select for these users a unique CQI value associated to a common SNR. The main issue here is to select from the set of SNRs within the group, a common SNR value. Let us denote it γ_c. The SNR selection strategy has a direct impact on the multicast throughput performance. In fact, the multicast throughput is given by

$$R_{mcast} = \frac{\beta_c(bits)}{D_{TTI}(sec)\tau_N}. \quad (18)$$

where β_c denotes the corresponding TBS associated to γ_c and τ_N the average number of transmissions with the memory-based approach and HARQ. A conservative link adaptation is limited by the Minimum SNR value among all the multicast users. Alternatively, link adaptation can be more or less aggressive to support larger TBSs but with a higher risk of packet retransmission. Table I recapitulates the considered CQI selection strategies.

TABLE I
LINK ADAPTATION STRATEGIES

Scheme	Description
Conservative	$\gamma_c = \min_{\{n=1..N\}}(\gamma_n)$
"Min SNR + 1"	$\gamma_c = \min_{\{n=1..N\}}(\gamma_n) + 1$
"square Min-Max SNR"	$\gamma_c = \sqrt{(\gamma_{min}\gamma_{max})}$
"Average SNR"	$\gamma_c = \left[\prod_{n=1}^{N} \gamma_n\right]^{\frac{1}{N}}$

1) Average Statistics over different user distributions: We consider 20 users that are randomly located in a cell. We perform 120 iterations, each one corresponds to a given user distribution. For each distribution, we compute the average number of transmissions obtained by the multicast link adaptation strategy and deduce the throughput. At the end, we average the throughput value over all the iterations. Results are given in Table II with the 95% confidence intervals (CI). The value of D_{TTI} is fixed to 2.10^{-3} sec. We see that the conservative scheme offers the best performance compared to the considered aggressive schemes.

scheme (bits)	Throughput (bps)
Conservative	$0.84\ 10^6\ \pm 3.5\%$
"Min SNR + 1"	$0.77\ 10^6\ \pm 3.6\%$
"square Min-Max SNR"	$0.66\ 10^6\ \pm 4\%$
"Average SNR"	$0.61\ 10^6\ \pm 3.5\%$

TABLE II
STATISTICS OF THE AVERAGE THROUGHPUT FOR DIFFERENT LINK ADAPTATION STRATEGIES.

IV. CONCLUSION

This paper has addressed SNR to CQI mapping and link adaptation for multicast considering different retransmission schemes.

We have shown that the mapping for multicast has to be more conservative than the case of unicast. This is due to the higher error coding rate that has to be applied. In this context, we have proposed a convenient CQI calculation scheme that better fits multicast, namely the *SNR-shifted* strategy. The shift depends mainly on the retransmission strategy and the number of multicast users. However, as the shift can not exceed 1 dB, the impact of the shifted strategy remains marginal in general.

Dealing with link adaptation, we have compared several strategies for bitrate allocation. We have shown that the conservative scheme offers the best performance. As such, the choice of the transmission parameters must take into account the worst case, as this determines the service coverage. Also, the conservative scheme offers the lowest packet loss rate and then, it seems more adequate for wireless real-time communications, in which retransmissions of erroneous packets may produce undesirable delays.

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