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# 1 Introduction

In RAN WG1#18 meeting, questions were raised on system simulation methodology for Asynchronous and Adaptive Incremental Redundancy (AAIR) scheme. In order to evaluate system capacity and performance, it is desirable to integrate link-level model with system-level simulations. A pragmatic approach is required to incorporate a *simplified* (but accurate) link-level model within the system-level simulation. In this contribution, we present aggregate $E_s/N_t$ method to determine the FER in system level simulations.

# 2 HARQ System simulations

In HARQ, the data rate can be selected by mapping the received SNR to the highest rate that guarantees 0.1% or better BLER from the AWGN curves. Note that the data rate does not take into account the HARQ/IR retransmissions.

An example of code block transmission requiring 2 retransmission attempts is shown in Table 1. At the time of the first sub-block transmission, the data rate is 3840 Kb/s (MCS7). This value for the data rate is obtained by mapping the $I_{or}/I_{oc}$ (5.0 dB) to a rate that guarantees 0.1% or better BLER (Figure 2.1). The decoding at the receiver fails and the second sub-block is sent at 1920 Kb/s (MCS6, mapped from 0.0dB $I_{or}/I_{oc}$). The decoding again fails and the third sub-block is sent at 7680 Kb/s (MCS8, mapped from 11.0dB $I_{or}/I_{oc}$). After receiving the third sub-block the decoding result is successful and the receiver sends back an ACK to the transmitter. The transmitter can then start the next code block transmission at a rate based on the $I_{or}/I_{oc}$ at the time of the transmission.

| Received $I_{or}/I_{oc}$ | Data rate [Kb/s] | Transmission attempt | Sub-block [bits] | CRC result |
|---|---|---|---|---|
| 5.0 dB | 3840 | 1 (New) | 6400 | NAK |
| 0.0 dB | 1920 | 2 (RTX) | 12800 | NAK |
| 11.0 dB | 7680 | 3 (RTX) | 6400 | ACK |

**Table 1. An example of code block (5120 bits) transmission requiring 2 retransmission attempts.**

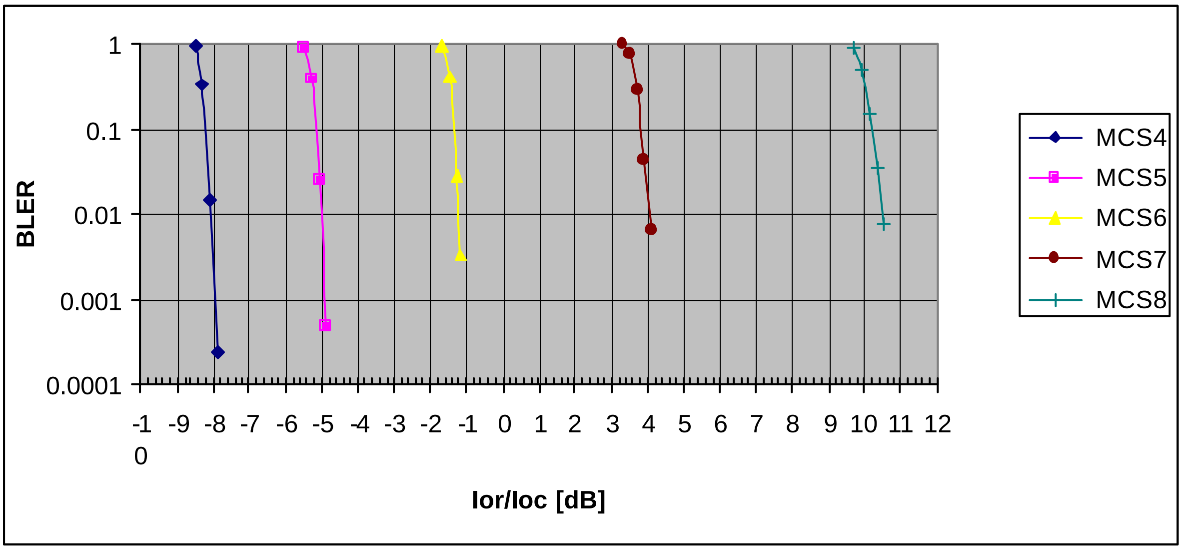


**Figure 2.1. BLER for 5120 bits code block**

# 3 Aggregate $E_s/N_t$ metric

The code block is encoded using a rate 1/m turbo code and, after appropriate repetition or puncturing, is transmitted over the channel. In case of puncturing, let 1/M denote the effective rate of the code. In case of repetitions, the effective rate of the code, once again denoted by 1/M, equals 1/m. Thus, in every case, $1/M ? 1/m$. The transmission duration is $n$ slots, with each slot being 0.667 ms long. We do not require that the $n$ slots be contiguous, and therefore this includes cases involving retransmissions. We assume as usual that the channel is static over each slot, and denote by $(E_s/N_t)_j, j ? 1,\ldots,n$, the SNR per modulation symbol for slot $j$. Furthermore, let $N_j, j ? 1,\ldots,n$, be the number of modulation symbols transmitted in slot $j$. We define the aggregate $E_s/N_t$ for the transmission, denoted $?_{E_s/N_t}$ as

$$?_{E_s/N_t} ? \frac{1}{N} ?? \sum_{j?1}^{n} N_j.(E_s/N_t)_j ??, \qquad (0.1)$$

where $N$ is a normalization factor. The expression within the square brackets in (0.1) represents the accumulated SNR over all the transmitted code symbols, and the normalization factor is introduced for convenience. In this contribution, we have set $N ? 1536$.

Intuitively, it is clear that $?_{E_s/N_t}$ is a good predictor of the BLER for an AWGN channel. The relationship between $?_{E_s/N_t}$ and BLER will, of course, depend on the effective coding rate 1/M, and will be denoted by $f_M$ for convenience. The subscript in $f_M$ denotes the inverse of the effective coding rate. Note that $f_M$ can easily be obtained through simulations. Additionally, the difference in the relationships $f_{M_1}$ and $f_{M_2}$ for two distinct effective coding rates $1/M_1$ and $1/M_2$ is essentially due to the difference in the coding gain. We are misusing accepted terminology when using the term "coding gain" here. To illustrate the relevant definition of coding gain, we present a simple example. Suppose the Es/Nt required in order to achieve a BLER of 0.001 over an AWGN channel with an effective code rate of ½ is $?$ dB. If we repeat the rate ½ code twice, then the Es/Nt required in order to achieve the same BLER is going to be $?$ -3dB. If, however, instead of simple repetition, we construct a good rate ¼ code, then the $E_s/N_t$ required would be $? ? ? ? ?$ dB, where $? ? ?$. Thus, we gained $?$ dB over the pure repetition code as a result of constructing a good rate ¼ code. This term $?$ is what we refer to as coding gain. In general, if $?_?$ and $?_?$ dB is the $E_s/N_t$ required to achieve a BLER of 0.001dB at coding rates of $1/M_1$ and $1/M_2$, respectively, and $M_1 ? M_2$, then the coding gain when using the rate $1/M_2$ code is $?_? ? ?_? ? 10\log_{10} ?\frac{M_2}{M_1}?$. Therefore, if one knows

1. $f_{M_1}$, and

2. the difference in the coding gain ( ? ? dB, say) when using effective code rates $1/M_1$ and $1/M_2$,

then $f_{M_2}$ is obtained from $f_{M_1}$ by using a fudge factor of ? when calculating the aggregate Es/Nt.

We now turn to the performance of the predictor for a wireless channel at high and low Doppler for various cases.

## 3.1 Low Doppler (less than 30Hz)

The method used to predict block error rate (BLER) depends on the modulation used.

### 3.1.1 QPSK Modulation

In this case, for a given effective rate 1/M, the functional relationship $f_M$ between $?_{E_s/N_t}$ and BLER for an AWGN channel can be used to predict BLER for a fading channel. We evaluate the performance of the predictor using the following two measures:

1. Difference in the actual and predicted BLER at different average Es/Nt. In particular, we look at the prediction error percentage, which we define as

$$\frac{(\text{Actual number of block errors } ? \text{ Predicted number of block errors})}{\text{Total number of blocks transmitted}}.100 \quad (0.2)$$

*The motivation behind this measure is as follows. The actual throughput seen at a given Es/Nt is*

$$?1 ? \frac{\text{Actual number of block errors}}{\text{Total number of blocks transmitted}}?(\text{Peak rate}),$$

while the predicted throughput is

$$?1 ? \frac{\text{Predicted number of block errors}}{\text{Total number of blocks transmitted}}?(\text{Peak rate}).$$

Therefore, the difference in actual throughput and predicted throughput is

$$\frac{(\text{Actual number of block errors } ? \text{ Predicted number of block errors})}{\text{Total number of blocks transmitted}}(\text{Peak rate}).$$

Normalizing with respect to peak rate, and taking a percentage yields the expression in (0.2).

2. Number or percentage of "Catastrophic Errors." For an AWGN channel and a given effective coding rate, the BLER is almost 0 if $?_{E_s/N_t} ? T_0$ dB, and the BLER is 1 if $?_{E_s/N_t} ? T_1$ dB. For turbo codes, $T_0 ? T_1 ? 1$ dB. For the fading channel, we declare a "catastrophic error" if one of the following two events occur

   ?? $?_{E_s/N_t} ? T_0$ AND the block is actually in error, or

   ?? $?_{E_s/N_t} ? T_1$ AND the block is actually NOT in error.

   The significance of a catastrophic error is as follows. The aggregate $E_s/N_t$ metric only captures a first order statistic of the channel variations. If the second order variations of the channel were to play a significant role in determining BLERs, then $?_{E_s/N_t}$ would prove to be insufficient in characterizing BLERs, and this, in turn, would lead to a large number of catastrophic errors. Few catastrophic errors, therefore, imply that the second order statistics of the channel are not important as long as $?_{E_s/N_t} ? T_0$ or $?_{E_s/N_t} ? T_1$. Since $T_0 ? T_1 ? 1$ dB (i.e., small), this would also imply that $?_{E_s/N_t}$ is a sufficient for predicting BLERs.

The performance of the predictor, and the corresponding simulation assumptions, is shown in Table 2 and Table 3, respectively.

**Table 2 Performance of Predictor at low Doppler for QPSK**

| Average C/I | Actual BLER | Predicted BLER | Prediction Error (%) | Catastrophic Errors |
|---|---|---|---|---|
| -2 | 0.53572 | 0.5274 | 0.832 | 0 |
| -1 | 0.45844 | 0.45048 | 0.796 | 0 |
| 0 | 0.3828 | 0.37512 | 0.768 | 0 |
| 1 | 0.32224 | 0.31412 | 0.812 | 0 |
| 2 | 0.26132 | 0.25536 | 0.596 | 0 |
| 3 | 0.21376 | 0.20916 | 0.46 | 0 |
| 4 | 0.1706 | 0.1656 | 0.5 | 0 |
| 5 | 0.13764 | 0.134 | 0.364 | 0 |
| 6 | 0.1118 | 0.10792 | 0.388 | 0 |

**Table 3 Simulation Assumptions**

| | |
|---|---|
| Doppler | 10Hz |
| Base turbo coding rate | 1/5 |
| Effective coding rate (after puncturing) | 1/4 |

In summary, it was verified that $?_{E_s / N_t}$ can be used to accurately predict the BLER at bw Dopplers for QPSK modulation if $1/M \; ? \; 2/3$. It is unclear how well the predictor will perform for larger values of 1/M. For larger values, the second order variations of Es/Nt play an increasing role in determining the BLER, and therefore, $?_{E_s / N_t}$ may not be sufficient. We strongly recommend that the performance of the predictor be independently verified in these cases. If the performance is unsatisfactory, then the pair

$$?? _{E_s / N_t}, \; g \, ?(E_s / N_t)_1, \ldots, (E_s / N_t)_n \, ? \qquad (0.3)$$

should be used for predicting BLER, where $g \, ?(E_s / N_t)_1, \ldots, (E_s / N_t)_n \, ?$ is some function that captures the second order variations of Es/Nt. Two examples of the function $g$ which were seen to perform well are

1. The coefficient of variation of Es/Nt, and
2. The aggregate of the worst $n/2$ slot Es/Nt.

Finally, since the functional relationship $f_M$ between $?_{E_s / N_t}$ and BLER over an AWGN channel depends only on the effective coding rate 1/M, it follows that this method applies both to Chase combining and pure incremental redundancy.

### 3.1.2 Higher Order Modulations

In case of Chase combining, if modulation symbol combining is done before demapping to soft bits (which are then input to the Turbo decoder), the aggregate Es/Nt estimator continues to perform well. If, however, the combining is done at the bit-level, then it becomes necessary to introduce fudge factors. This is also true when a combination of incremental redundancy and combining is used. We explain below the necessity for these fudge factors.

A penalty in Es/Nt is incurred when demapping from higher order modulation symbols to soft bits. For example, if Es/Nt is the SNR for a 16-QAM symbol, then, the SNR for the demapped bits is $? \, (Es/Nt)/(4? \, ?$, where $? \; ??$ is the "demapping penalty." More importantly, ? is a non-linear function of the symbol SNR. This is evidenced from Table 4 which shows the Es/Nt required for QPSK and 16-QAM to achieve a BLER of 0.001 over an AWGN channel. The base turbo code rate was 1/5, and coding rates lower than 1/5 were obtained by repetition. In the case of 16-QAM, the combining of repeated symbols were done at the bit-level, i.e., after the demapping operation.

**Table 4 16-QAM performance loss**

| Coding rate | QPSK | 16-QAM |
|---|---|---|
| 1/8 | -5.8dB | -1dB |
| 1/16 | -8.8dB | -4dB |
| 1/32 | -11.8dB | -6.8dB |
| 1/64 | -14.8dB | -8.6dB |
| 1/128 | -17.8dB | -9.4dB |
| 1/256 | -20.8dB | -9.5dB |

Note that for QPSK the Es/Nt required to achieve the target BLER reduces by 3dB if the effective coding rate is reduced by a factor of 2 (as can be expected). By contrast, this is not true in the case of 16-QAM modulation. This behavior is due to the fact that the demapping penalty increases as the SNR reduces.

The demapping penalties ? , which are functions of Es/Nt, constitute the fudge factors. So, for higher order modulations, the aggregate Es/Nt is given by:

$$?_{E_s/N_t} ? \frac{1}{N} ?\sum_{j?1}^{n} N_j.(E_s/N_t)_j.?_{(E_s/N_t)_j} ?. \quad (0.4)$$

The term $(E_s/N_t)_j.?_{(E_s/N_t)_j}$ denotes the aggregate effective SNR for the demapped bits obtained from one modulation symbol when the symbol SNR is Es/Nt. The term $N_j.(E_s/N_t)_j.?_{(E_s/N_t)_j}$ then represents the aggregate Es/Nt for all the demapped bits in slot j. For an effective coding rate 1/M, the "adjusted" aggregate Es/Nt in (0.4), in conjunction with the functional relationship $f_M$ obtained when using QPSK modulation over an AWGN channel, can now be used to predict BLER for higher order modulations.

The following table indicates the performance of the aggregate Es/Nt predictor after the introduction of fudge factors for 16-QAM, when the combining of repeated symbols (if any) were done at the bit-level.

**Table 5 Prediction Performance for 16-QAM**

| Average C/I | Actual BLER | Predicted BLER | Prediction Error (%) | Catastrophic Error (%) |
|---|---|---|---|---|
| -5 | 0.930246 | 0.907207 | 2.303816 | 4.539637 |
| -4 | 0.865345 | 0.847528 | 1.781782 | 1.705706 |
| -3 | 0.786475 | 0.783712 | 0.276265 | 0.264254 |
| -2 | 0.70764 | 0.72952 | -2.188 | 0.06 |
| -1 | 0.634074 | 0.665946 | -3.18719 | 0.02002 |
| 0 | 0.56254 | 0.586883 | -2.43434 | 0.028027 |

| | | | | |
|---|---|---|---|---|
| 1 | 0.468501 | 0.468821 | -0.032 | 0.008 |
| 2 | 0.38708 | 0.36308 | 2.4 | 0.016 |
| 3 | 0.29312 | 0.24852 | 4.46 | 0.004 |
| 4 | 0.20284 | 0.15228 | 5.056 | 0.016 |
| 5 | 0.13716 | 0.09276 | 4.44 | 0.052 |
| 6 | 0.07604 | 0.04172 | 3.432 | 0.084 |
| 7 | 0.05036 | 0.02612 | 2.424 | 0.156 |
| 8 | 0.02584 | 0.01204 | 1.38 | 0.204 |
| 9 | 0.01404 | 0.00584 | 0.82 | 0.16 |

**Table 6 Simulation Assumptions**

| | |
|---|---|
| Doppler | 10Hz |
| Base turbo coding rate | 1/5 |
| Effective coding rate | <1/4 |

## 3.2 High Doppler

### 3.2.1 QPSK Modulation

At high Doppler, it may be necessary to introduce a fudge factor when using $?_{E_s/N_t}$ to predict BLERs. In general, using the functional relationship $f_M$ between $?_{E_s/N_t}$ and BLER obtained from the AWGN channel to predict BLERs at high Doppler results in an under-estimation of BLERs. Using fudge factors easily solves the problem. Thus the modified aggregate Es/Nt is given by

$$?_{E_s/N_t} ? \frac{1}{N?} ? ? \sum_{j?1}^{n} N_j.(E_s/N_t)_j ?, \qquad (0.5)$$

where $? ? ?$ is the fudge factor. From our simulations at 100Hz Doppler, $?$ was seen to lie in the range 0.3 to 0.6dB. The following table shows the performance of the predictor at 100Hz Doppler for an effective code rate of ¼; $?$ was chosen to be equal to 0.55dB.

**Table 7 Performance at high Doppler with and without fudge factors**

| Average Es/Nt | Actual BLER | Predicted BLER (without fudge factor) | Predicted BLER (with fudge factor) | Prediction error (%) (without fudge factor) | Prediction error (%) (with fudge factor) | Catastrophic Error (%) |
|---|---|---|---|---|---|---|
| -2 | 0.524 | 0.46528 | 0.52412 | 5.872 | -0.012 | 0.610163 |
| -1 | 0.41044 | 0.35784 | 0.4082 | 5.26 | 0.224 | 0.779645 |
| 0 | 0.30176 | 0.25596 | 0.29944 | 4.58 | 0.232 | 0.796142 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 0.22156 | 0.1864 | 0.22236 | 3.516 | -0.08 | 0.697233 |
| 2 | 0.15508 | 0.12932 | 0.1544 | 2.576 | 0.068 | 0.558275 |
| 3 | 0.11256 | 0.09104 | 0.11136 | 2.152 | 0.12 | 0.545293 |
| 4 | 0.07024 | 0.05688 | 0.06884 | 1.336 | 0.14 | 0.386084 |
| 5 | 0.04412 | 0.03524 | 0.04396 | 0.888 | 0.016 | 0.295639 |
| 6 | 0.03124 | 0.02488 | 0.03108 | 0.636 | 0.016 | 0.235677 |

**Table 8 Simulation Assumptions**

| | |
|---|---|
| Doppler | 100Hz |
| Base turbo coding rate | 1/5 |
| Effective coding rate (after puncturing) | 1/4 |

In conclusion, upon applying a fudge factor, $?_{E_s/N_t}$ can be used to accurately predict BLERs at high Doppler. The fudge factor, which, in general, depends on the effective code rate 1/M, the code block size, and the Doppler, has to be determined through simulations.

As mentioned in Section 3.1.1, the conclusions above hold as long as the effective code rate is smaller than 2/3. For higher effective code rates, it may be necessary to use the estimator in (0.3).

### 3.2.2 Higher Order Modulations

We first consider the case when the modulation symbols are combined prior to demapping to soft bits. In this case, a fudge factor similar to ? in (0.5) needs to be introduced in calculating $?_{E_s/N_t}$. This fudge factor accounts for the penalty due to high Doppler, and needs to be determined through simulations.

In the case where the modulation symbols are first demapped to soft bits and then combined, fudge factors similar to the ?'s in (0.4) need to be introduced to account for the demapping penalty. Since these values will also account for the penalty due to high Doppler, a separate fudge factor like ? is not necessary.

## 3.3 Other miscellaneous considerations

All the results presented above were for a single-path Rayleigh fading channel, with ideal channel estimation, and MAX* turbo-decoding. For a multi-path Rayleigh fading channel, when the signals along each path are "maximum-ratio-combined," the Es/Nt of the combined signal is the sum of the Es/Nt along each path. Therefore, the aggregate Es/Nt is going to be the sum of the aggregate Es/Nt along each path. If, however, the signals are not "maximum-ratio-combined," then the Es/Nt of the combined signal is no longer the sum of the Es/Nt along each path, and is, in fact, less than the sum. This effect can be accounted for by introducing a fudge factor. Thus, the aggregate Es/Nt for QPSK modulation at low Doppler for a $k$-path Rayleigh fading channel can be calculated as

$$?_{E_s/N_t} ? \frac{1}{N?} \sum_{l=1}^{k} ? \sum_{j?1}^{n} N_j.(E_s/N_t)_{j,l} ?, \qquad (0.6)$$

where $(E_s/N_t)_{j,l}$ is the SNR in slot $j$ on path $l$, and ? ? ? is a fudge factor which accounts for the fact that the signals along the various paths are not being maximum-ratio-combined. However, if the signals are maximum-ratio-combined, then ? ? 1.

Non-ideal channel estimation and MAX turbo-decoding (instead of MAX*) lead to other penalties which can also be accounted for introducing additional fudge factors. The values of each of these fudge factors need to be determined. We believe that all these penalties will not amount to greater than 1dB, and could be ignored for the sake of convenience.

# 4 Conclusion

A methodology to integrate link-level model with system-level simulations for HARQ performance evaluation is discussed. Further details will be provided in the future contributions for the case when the HARQ transmissions at different modulations for the same code block need to be combined.

# 5 References

[1] "$A^2$IR - An Asynchronous and Adaptive HARQ scheme for HSDPA", Lucent Technologies, TSG-RAN WG1#18(01) 0080, Boston, USA.