Performance Analysis of Link Adaptation in LTE Systems

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***Abstract*—In this paper we focus on finding a suitable Link Adaptation (LA) algorithm which is implemented as Channel Quality Indicator (CQI) selection technique in the 3GPP Long Term Evolution (LTE) system. The potential of Link Adaptation in the LTE system is not fully exploited. Therefore in our study, we compare the performances from different LA algorithms in the LTE system. The presented LA algorithms are EESM, Raw-BER and MMIB which utilize the post processing SINRs (Signal-to-Interference-and-Noise power Ratio) to compute the effective SNR (Signal-to-Noise power Ratio), uncoded bit error probability and mutual information as mapping function, respectively. We present our simulation results and show that the EESM algorithm can significantly improve the performance of the whole system both in the SISO case and the MIMO case.**

***Index Terms*—LTE; Link Adaptation; EESM.**

I. Motivation and Problem statement

In real world scenarios, the wireless channel varies over time. Thus, link adaptation can be used to deal with a fading channel in order to sustain a reliable communication and to increase throughput of a system. As shown in Fig. 1, a basic principle of LA is to select one of the CQIs according to the channel condition or Channel State Information (CSI).

At the receiver, when CSI is unknown, the most easy way to estimate the Packet Error Ratio (PER) is simply dividing the number of erroneous packets by a total number of received packets in a given time period. However, this approach requires long time to converge especially at low PER. This kind of approach is defined as Slow Link Adaptation (SLA) since it takes a lot of time to accumulate enough packets to estimate the PER. On the other side, if CSI is available at the receiver, a better way to estimate the PER can be found which depends on CSI and will converge fast. Therefore, this kind of LA can be defined as Fast Link Adaptation (FLA) which estimates a suitable CQI value depending on the current channel condition. Fig. 2 shows the difference between SLA and FLA. In a word, the FLA adapts the modulation order and coding scheme according to varying channel conditions in order to have high throughput compared to SLA. FLA is a closed loop mechanism which dynamically selects a suitable CQI value depending on the current channel realization whereas SLA is an open loop mechanism which selects a suitable CQI value depending on long term statistics.

Due to huge advantage of FLA compared with SLA, we decide to choose FLA algorithms as CQI selection technique

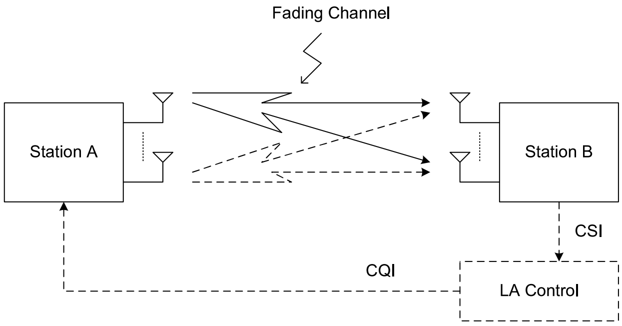

Fig. 1. Block diagram for Link Adaptation.

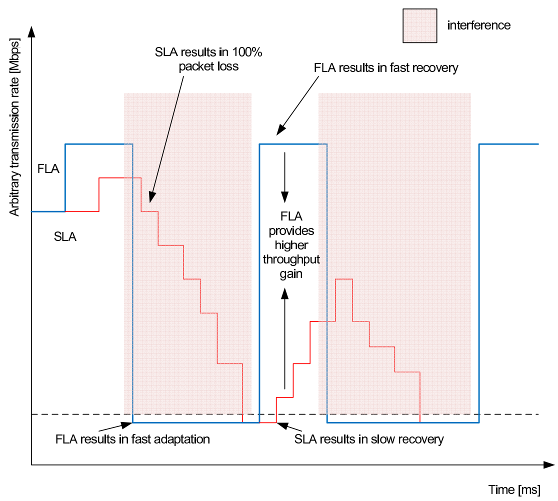

Fig. 2. Schematic highlighting the difference between SLA and FLA. Inspired from [1].

in the LTE system. Several approaches have been studied to select the CQI value such as:

- Instantaneous SNR [2],
- PER indicator method [3],
- Exponential effective SNR mapping (EESM) [4],
- Raw or uncoded bit error rate mapping (RawBER) [5],
- Mutual information per coded bit mapping (MMIB) [6].

Although a lot of work have been done on CQI selection for link adaptation, only a few studies are focused on LTE systems. Our work intends to find the most suitable algorithm and investigate the possibility of optimizing some of the

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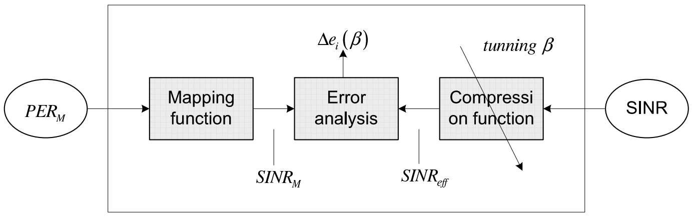

Fig. 3. The concept of obtaining β.

TABLE I
β VALUE FOR ALL CQI INDEX

CQI Index	β value	CQI Index	β value
1	1.84	3	1.35
4	1.56	5	1.50
6	1.59	7	3.40
8	4.13	9	5.66
10	9.26	11	14.62
12	20.63	13	24.54
14	28.99	15	35.44

algorithms to deliver higher throughput for an LTE system.

II. APPROACH

A. EESM

A well-known approach to link performance modeling and link quality prediction is the EESM method, which computes an effective SNR (also referred to as AWGN equivalent SNR) by taking the individual subcarrier SINRs as input and using an exponential combining function:

$$\mathrm{SNR}_{\mathrm{eff}} = -\beta \log\left(\frac{1}{N_{ss}N_{sd}}\sum_{j=1}^{N_{ss}}\sum_{k=1}^{N_{sd}}\exp\left(\frac{-\mathrm{SINR}_j\left[k\right]}{\beta}\right)\right), \tag{1}$$

where N_{ss} indicates the number of spatial streams, N_{sd} indicates the number of subcarriers and the parameter β is used to fit the model to the System performance. Once the effective SNR is computed, the packet error ratio (PER) is obtained from looking up an AWGN performance curve. This approach has been widely applied to OFDM link layers and is based on the Union-Chernoff bound of error probabilities [4].

The empirical parameter β is a key point in the EESM algorithm. A validation approach to estimate β is depicted in Fig. 3 [7]. For each channel realization, we can obtain a certain PER from simulations. Then we map this PER in the AWGN performance curve to get an SNR value, which is named as measured SNR. On the other side, for the same channel realization, the EESM algorithm is used to find an effective SNR from all individual subcarrier SINRs. Afterwards, the least-squares approach is applied to normalized SINR differences in the log domain given in the following equation:

$$\beta_{\mathrm{opt}} = \arg\min_{\beta}\sum_{i=1}^{N_c}\mid\triangle\, e_i\left(\beta\right)\mid^2, \tag{2}$$

where

$$\triangle e_i\left(\beta\right) = \log\left(\mathrm{SINR}_{\mathrm{eff}}^i\left(\beta\right)\right) - \log\left(\mathrm{SINR}_M^i\right)\ \forall i = 1,2,...,N_c, \tag{3}$$

and N_c is the number of different channel realizations considered for the optimization process, SINR_M^i is the mapped SINR for the ith channel realization from the simulated PER, and $\mathrm{SINR}_{\mathrm{eff}}^i\left(\beta\right)$ is the estimated SINR for the given β and ith channel realization.

It is worth to mention that, not all collected data from link level simulations is relevant or sufficiently reliable and thus it is reasonable to limit the set of data to a certain PER interval, e.g. $\mathrm{PER}_M \in [0.01, 0.95]$. In our work, a set of β values is obtained with more than 500 simulation runs for each CQI point, which are shown in Table I.

B. RawBER

Another approach is to use the raw (uncoded) BER as Link Quality Metric (LQM). In RawBER mapping, an effective RawBER is found by averaging over all probabilities of uncoded bit errors at each subcarrier [5]. A one-dimensional look-up table should be prepared beforehand for an AWGN channel which can take the raw (uncoded) bit error ratio as an input and corresponding PER as an output for a given CQI value.

The effective raw BER is given by:

$$\mathrm{RawBER}_{\mathrm{eff}} = \frac{1}{N_{ss}N_{sd}}\sum_{j=1}^{N_{ss}}\sum_{k=1}^{N_{sd}}\mathrm{RawBER}_j\left[k\right], \tag{4}$$

where $\mathrm{RawBER}_j\left[k\right]$ is the raw bit error probability of the jth spatial stream and kth subcarrier for a given modulation. In the LTE system, unequal modulation types can be used in different spatial streams, RawBER will be evaluated for each spatial stream and afterwards combined in one scalar value as:

$$\mathrm{RawBER}\left[k\right] = \frac{\sum_{j=1}^{N_{ss}} b_j \mathrm{RawBER}_j\left[k\right]}{\sum_{j=1}^{N_{ss}} b_j}, \tag{5}$$

where b_j is the number of bits per symbol.

C. MMIB

In [6], a mutual information based LQM is suggested as a good metric for system level simulations for the standard IEEE 802.16e. The mean mutual information per symbol $I_{\mathrm{mean}}^{\mathrm{symbol}}$ is found here by averaging over all the mutual information values for each subcarrier and spatial stream:

$$I_{\mathrm{mean}}^{\mathrm{symbol}} = \frac{1}{N_{ss}N_{sd}}\sum_{j=1}^{N_{ss}}\sum_{k=1}^{N_{sd}} I_j^{\mathrm{symbol}}\left[k\right]\left(\mathrm{SINR}_j\left[k\right]\right), \tag{6}$$

where $I_j^{\mathrm{symbol}}\left[k\right]$ is the mutual information per symbol which depends on the modulation type (QPSK, 16QAM, 64QAM in LTE system). The mutual information over uncoded M-ary PSK and QAM signals, with block-wise hard-decision can be estimated by considering the binary symmetric channel with the transition probabilities $\overline{p_b}$ and $1-\overline{p_b}$, respectively.

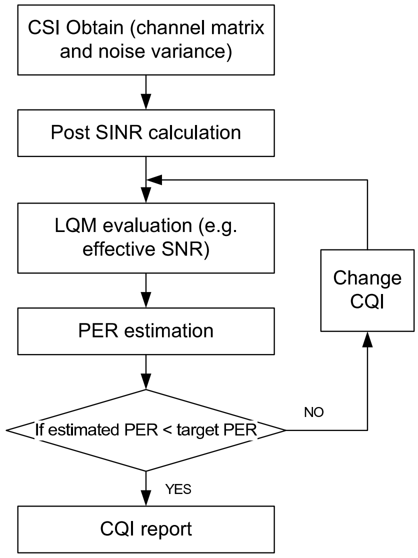

Fig. 4. General implementation recipe.

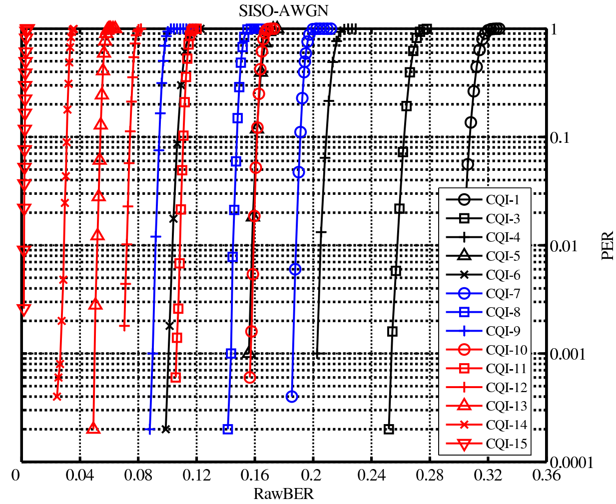

Fig. 5. Relation between RawBER and $\mathrm{PER}_{\mathrm{ref}}$.

Therefore, in AWGN channel, the mutual information can be calculated by [8] as:

$$I_M\left(\mathrm{SNR}\right) = 1 + \overline{p_b} \cdot \log_2 \overline{p_b} + \left(1 - \overline{p_b}\right) \cdot \log_2\left(1 - \overline{p_b}\right), \quad (7)$$

where $\overline{p_b}$ is the probability of error transition and derived from [9] [10].

D. Algorithm Outline

The general implementation concept of a fast link adaptation algorithm is shown in Fig. 4.

To make the process more clear, the steps of the RawBER algorithm are shown as an example in detail.

(1) Firstly, the channel matrix $\mathbf{H}\left[k\right]$ and noise variance should be obtained depending on current channel condition.
(2) With channel matrix and nominal SNR, the post-processing SNRs are calculated for all the subcarriers and spatial streams as given in following equation:

$$\mathrm{SINR}_j\left[k\right] = \frac{1}{\left[\left(\left(\frac{E_s}{N_0}\right)\frac{1}{N_T}\mathbf{H}^{\mathrm{H}}\left[k\right]\mathbf{H}\left[k\right] + \mathbf{I}_{N_T}\right)^{-1}\right]_{jj}} - 1. \quad (8)$$

(3) Then, with the calculated SINRs it is possible to estimate the RawBER for each stream, this can be done by calculating the average of the RawBER of all the subcarriers as given in equation (9),

$$\mathrm{RawBER}_j = \frac{1}{N_{sd}} \sum_{k=1}^{N_{sd}} \mathrm{RawBER}_j\left[k\right]. \quad (9)$$

(4) As mentioned before, different streams can have different modulation types which is defined in LTE standard. Therefore the effective RawBER can be obtained by combining all the data streams into a single stream as:

$$\mathrm{RawBER}_{\mathrm{eff}} = \frac{\sum_{j=1}^{N_{ss}} b_j \mathrm{RawBER}_j}{\sum_{j=1}^{N_{ss}} b_j}. \quad (10)$$

(5) The computed effective RawBER is mapped to a corresponding reference PER for the current modulation and coding scheme using the CQI search loop and a pre-defined look-up table as shown in Fig. 5.
(6) The CQI search is performed by repeating steps (3) to (5) until the current CQI renders PER less than or equal to the threshold of the target PER, e.g. 10%.
(7) Finally, the selected CQI value will be reported to the transmitter.

III. Simulation Results

A. Simulation Parameters

For the simulations presented in this section, it has been assumed ideal channel estimation, a MIMO configuration of 4 antennas at the transmitter and 2 antennas at the receiver and also a SISO configuration. The channel model is taken from the LTE standard [11]. In our simulation, we choose the Extended Vehicular A (EVA) channel model which exhibits medium delay spread environments and medium Doppler frequencies, where its power delay profile is shown in Fig. 6. Table II summarizes the parameters used for the simulations.

B. Performance Lower Bound

To analyze how link adaptation algorithms perform in the whole system chain, we should find out a reasonable lower bound for comparison. FLA adapts the CQI according to varying channel conditions in order to achieve a higher throughput compared to SLA. Therefore, we choose the performance of SLA as the lower bound of FLA.

As we mentioned before, SLA ensures a certain PER by changing the CQI slowly considering long term statistics [1]. At this point, SLA will be equivalent to shift between the fixed modulation order and coding scheme, which also means the fixed CQI value in LTE system. So, we consider the throughput for the fixed CQI envelope with PER constraint to be equal to the ideal throughput for SLA. Where the PER constraint means

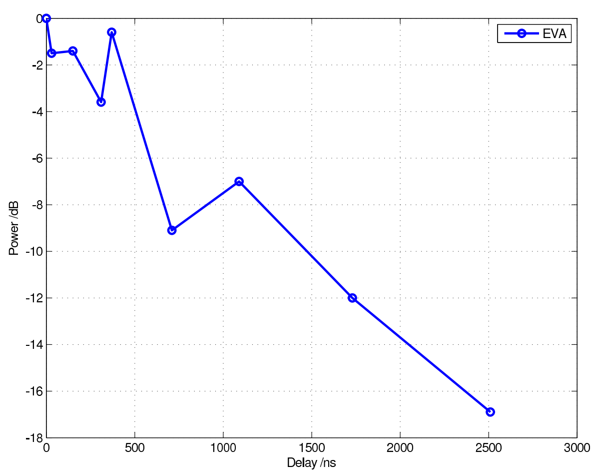

Fig. 6. EVA channel power delay profile.

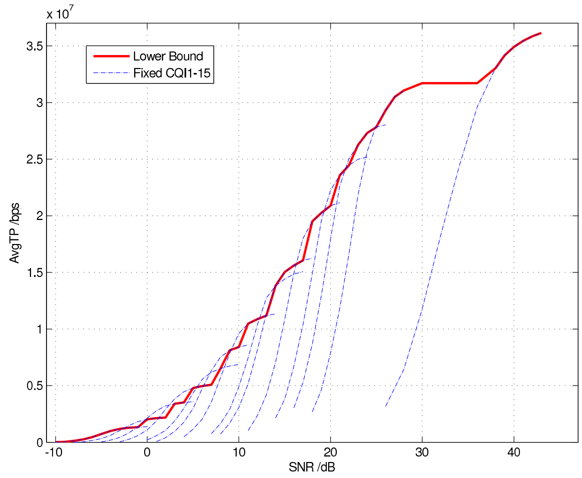

Fig. 7. Performance lower bound. (AvgTP stands for average throughput)

TABLE II
SUMMARY OF SIMULATION CONFIGURATIONS

Parameter	Value
Transmission time interval (TTI) duration	1 ms
Transmission bandwidth	10 MHz
FFT bandwidth	15.36 MHz
FFT size	1024
Number of OFDM symbols per TTI	14
Channel coding	Turbo code
Channel estimation	Perfect
Antenna schemes	SISO 1x1 and MIMO 4x2
SISO receiver	One tap equalizer
MIMO receiver	ZF, MMSE and Alamouti
Number of used subcarriers for current user	600
Number of TTI blocks between CQI updating	10
Number of simulated TTI blocks	1000
Target PER	10 %

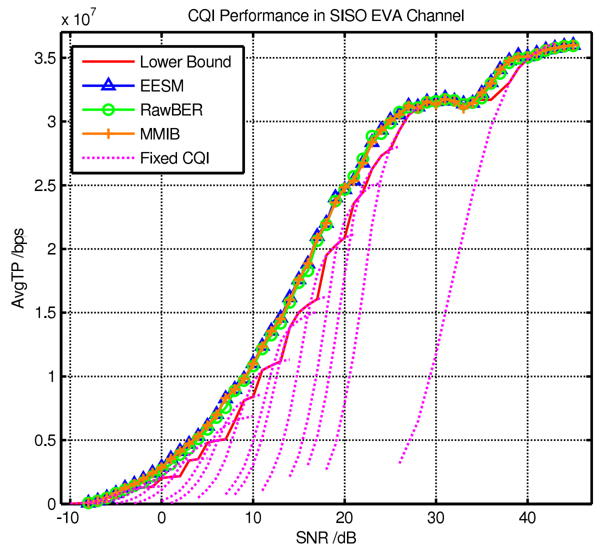

Fig. 8. Evaluation of throughput with different CQI selection algorithms in the SISO case.

that the observed PER should be below a certain threshold, e.g. the target PER less than 10%. Fig. 7 shows the throughput lower bound of link adaptation and the throughput of fixed CQI envelope with PER constraint in the SISO case.

C. Simulation Result

The system throughput and PER versus SNR for the three different link adapatation algorithms which have been discussed beforehand are shown in this section. Fig. 8 shows the throughput of the fixed CQI, the lower bound and the system throughput using three FLA algorithms as CQI selection method in the SISO case. The evaluation of PER for the SISO case is shown in Fig. 9. The evaluation of throughput and PER in the MIMO case are shown in Fig. 10 and Fig. 11, respectively.

IV. CONCLUSION

From simulations we could find out that the performances of these three algorithms are approximately the same for a SISO antenna configuration. We can get in average a throughput gain of 15% compared with the lower bound of the whole system chain. We also observe that the gain is larger in the mid SNR region, where the FLA algorithm has more different CQIs to choose. FLA algorithms and lower bound merge at low and high SNR regions because the selection algorithms are bounded by the available CQI values.

From Fig. 10 and Fig. 11 we can conclude that the RawBER method is not suitable for the MIMO case. Since in a MIMO system the influence of the channel on the link quality (PER) is more complex and raw BER is more sensitive to the channel state, using uncoded BER as link quality prediction metric decreases the system performance. However, principal reason of a performance loss fot the RawBER algorithm in the MIMO case is the drawback in algorithm itself. In the RawBER algorithm, the effective RawBER is obtained by

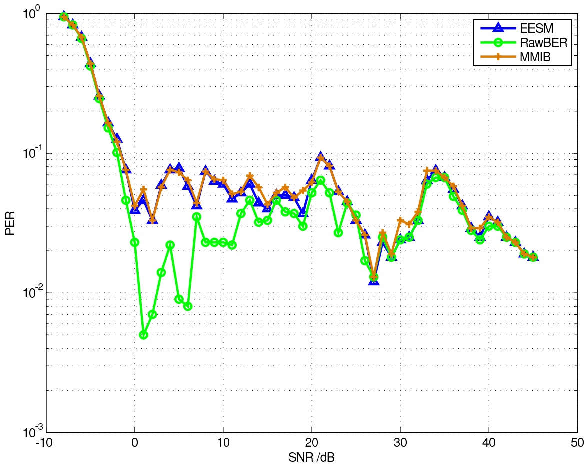

Fig. 9. Evaluation of PER with different CQI selection algorithms in the SISO case.

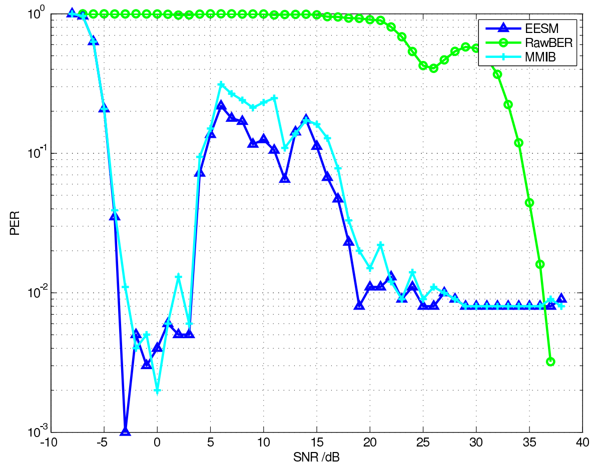

Fig. 11. Evaluation of PER for different CQI selection algorithms in MIMO case.

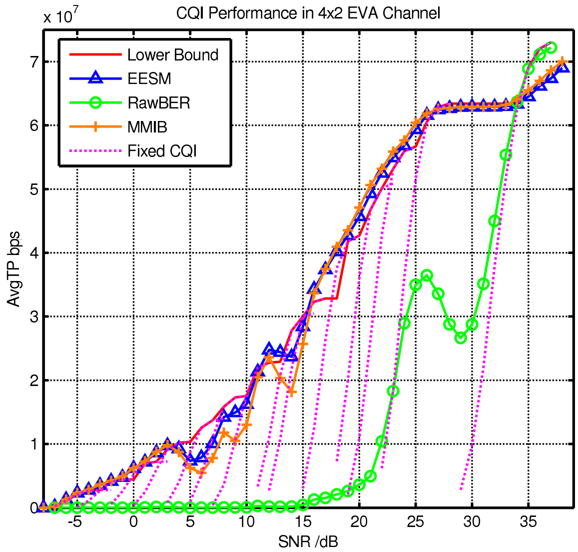

Fig. 10. Evaluation of throughput for different CQI selection algorithms in MIMO case.

simply averaging RawBERs of different streams and subcarriers. This averaging operation extremely corrupt the SINRs distribution, which make the effective mapping function less accuracy.

From Fig. 10 and Fig. 11 we can see that EESM and MMIB have approximately equal estimation accuracy. However, the throughput gain with link adaptation for the MIMO case is not as large as in the SISO case. We also found that in the modulation switching area e.g. from QPSK to 16QAM, the throughput loss with the MMIB algorithm is higher than that with the EESM method. The reason can be that in this case the optimization variable β is working better for EESM than the MI approximate mapping function in MMIB.

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