CQI Measurement and Reporting in LTE: A New Framework

Kambiz Homayounfar and Bijan Rohani†

PHYBIT, INC.
AM Building 5F, 2-3-3 Higashi Gotanda, Shinagawa, Tokyo 141-0022, Japan
E-mail: kambiz@phybit.com

†PHYBIT, INC.
10-10 Cendex Center, 120 Lower Delta Road, Singapore 169208
E-mail: bijan@phybit.com

Abstract One problem with channel quality measurement in Long-Term Evolution (LTE) is how to define channel quality. Another is how to report it. We present a new framework for calculating the Channel Quality Indicator (CQI) and describe methods for efficient CQI reports that comply with LTE signaling schemes.

Key words LTE, CQI, AMC

1 Introduction

Communication over a time-varying radio channel is subject to radio channel impairments such as additive white Gaussian noise (AWGN), flat and frequency-selective fading, and log-normal shadowing. These introduce losses in the received information and degrade the quality of the delivered service. If channel becomes too bad and the link becomes useless, and if it becomes too good then the link is using up resources unnecessarily. In time-varying radio channels both these scenarios can arise in the life of a connection. Different applications require different quality of service (QoS) levels: what is good for voice may not be good for video. To ensure that the QoS for a specific application is met under varying radio channel conditions, radio link adaptation techniques become necessary. This involves radio link quality measurement and control. Measurement of the radio link quality is mainly done at the receiver and entails estimation of one or a number of radio link measures such as the received signal strength (RSS), the signal-to-noise ratio (SNR), the bit-error-rate (BER) before or after the channel decoder, etc. The control part of radio link adaptation involves adapting the modulation, coding, and/or power of the transmitted signal within system capabilities and constraints based on the radio link quality measurements. Radio link adaptation at the transmitter is done in response to link adaptation commands/request in an attempt to maintain QoS close to its intended target value. Effectiveness of radio link adaptation reduces with increased time variation of the channel. The commands/requests can become outdated in fast channels and result in irrelevant adjustments in the transmitted signal parameters.

In this paper, a new framework, namely, statistical radio link quality control (SRLQC), for the design of ACM control algorithms is disclosed. The key difference between this method and the state-of-the-art is that SRLQC does not rely on an accurate mapping between SNR and BER to decide the best ACM scheme for the channel condition.

2 A New Framework for Radio Quality Control

The radio link quality is random in nature and can be represented by a random time-series. It should then be possible to apply statistical process control (SPC) to radio link adaptation. The following sections show how.

2.1 Statistical Process Control

SPC is a collection of tried-and-true methods from a blend of statistics and control engineering [1]. It has been successfully applied in industries such as industrial automation and chemical engineering for monitoring and control of sophisticated processes. In SPC, the output of a process is viewed as being random in nature, and provides powerful tools for monitoring and control of processes based on the statistics of the process.

In the context of SPC, a process is in either of the following two states:

- Under control: in this state the process is only affected by common causes. Common causes cannot be removed, and the process variations are only due to these common causes. The process in this state is stationary.
- Out of control: the process is affected by special causes. The process variations are due to both com-

mon and special causes in this state. The process is non-stationary in this state. In order to restore the process to the state of control, special causes must be identified and removed.

An example of a typical random process is shown in Figure 1. Here the samples of the process have been represented by the time-series x_k plotted against the time index k. For convenience, take x_k to be have a normal distribution (see Figure 2) with its Probability Density Function (pdf) given by $f(x_k)$. So x_k can vary randomly around its mean μ_x when the process in a state of control. In this state only common causes are present and the process is stationary. Furthermore, the sample values x_k lie in the interval $\mu_x \pm 2\sigma_x$ with a probability of 0.954, and fall in the interval $\mu_x \pm 3\sigma_x$ with a probability of 0.997. That is to say, if the process is in a state of control, its sample values must almost certainly fall within the $\mu_x \pm 3\sigma_x$ range. If it does not, something is wrong and adaptation is necessary.

The $\pm 3\sigma_x$ limits on the process variations are known as the action levels and define the boundaries beyond which the process is deemed to be out of control or non-stationary. Hence, action must be taken so that the process can return to a state of control. In practice, the $\pm 2\sigma_x$ are used for process monitoring. These are known as warning levels and, as the name suggests, can be used as alarms to indicate that the process is showing signs of going out of control (becoming non-stationary).

The process monitoring method illustrated in Figure 1 is known as a Shewhart chart. It is a simple and practical way of monitoring industrial processes. However, there are more powerful schemes that can be adopted depending on the needs of the process to be controlled.

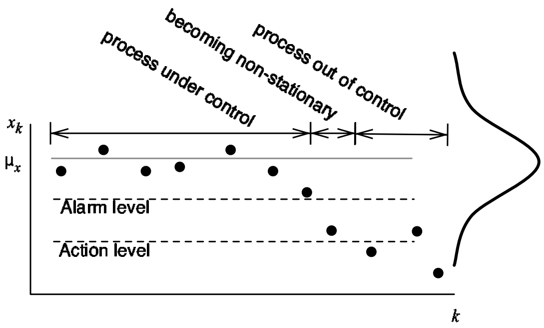

Figure 1: Example of monitoring the state of a process (shown as x_k) by comparing the observed time-series against control levels

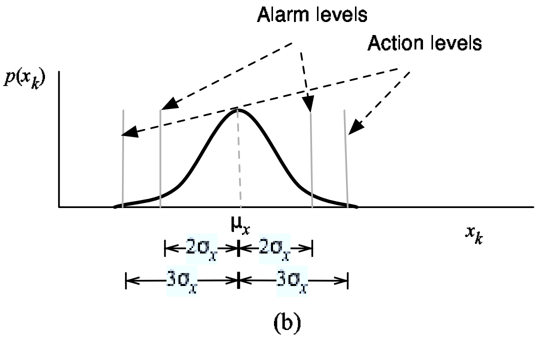

Figure 2: Control levels for a Normal Probability Distribution Function

3 Statistical Control of Radio Link Quality

We now describe how SPC concepts can be put to work for statistical radio link quality control (SRLQC). With the brief background given above on the SPC, it is possible to examine the function of radio link adaptation in the context of a statistical process control problem.

3.1 Link Adaptation

The radio link quality is random in nature and can be represented by a random time-series. When the link quality is under control, its variations are due to common causes, such as AWGN and hardware imperfections, that cannot be removed. The time-varying channel gain due to multi-path fading and shadowing, which constitute special cases, will have been removed in this state. The underlying statistical model in this case is that of the link quality in an AWGN channel. The link quality is stationary and samples vary around a constant mean value with a constant variance. The variations of the quality can be modeled by a pdf reflecting the receiver performance in an AWGN channel. The pdf parameters μ and σ are constants that characterize the link quality when it is under control. Conversely, when the link quality is out of control, channel gain variations due to fading and shadowing are present. As such, the link quality varies under the influence of these factors as well as AWGN. The link quality becomes non-stationary in this state. The non-stationarity can be better understood if the channel can be approximated as being quasi-static. In such a scenario, the transmission time is divided into intervals in which the channel gain is considered to be constant within each interval and variable between intervals. As such, the channel in each time interval behaves like an AWGN channel whose SNR depends on the per interval channel gain. The pdf that models the link quality variations changes from one time interval to the next giving rise to variations in the mean-value and variance of the link quality across the transmission time span, thus exhibiting non-stationarity.

3.2 The Quality Control Loop

A diagram showing the structure for implementing statistical control of radio link quality is Figure 3. Here TX Bits represent the information bits to be transmitted. The information could be audio, video, text, data, or a combination thereof.

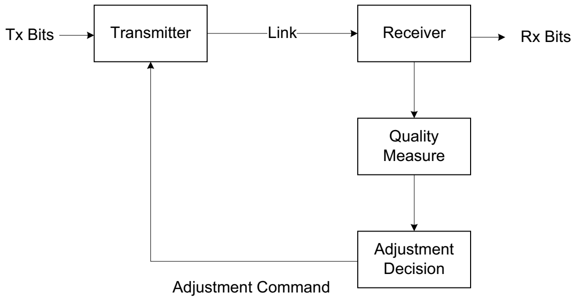

Figure 3: Statistical Control of Radio Link Quality

The functional block Transmitter represents a chain of physical layer functions that are performed on the TX Bits to prepare them for transmission over the radio link. These functions may include source coding, interleaving/channel coding, modulation, filtering and amplification. The specific parameters for the physical layer functions vary according to the wireless standard adopted for implementing the system. Nonetheless, the same principles for SRLQC apply regardless of the specifics of the standard. Link represents a radio channel. It provides a medium for the flow of information from Transmitter to Receiver. A radio channel can introduce a variety of impairments on the transmitted signal that may lead to loss of parts or all of the information. The functional block Receiver is responsible for recovering TX bits from the received signal on Link. It does so by applying the inverse physical layer functions corresponding to those applied in Transmitter. Ideally, the recovered bits RX bits are identical to TX Bits. In practice, however, a fraction of RX Bits is received in error leading to some information loss. The degree of loss that can be tolerated depends on the type of the transmitted information. The degree of loss introduced by Link is quantified by the block Quality Measure. In particular, in a time varying radio channel, the measured quality fluctuates with time. In such cases, link quality must be stabilized by calculating adequate adjustments to be carried out at the transmitter. This is implemented by the block indicated as Adjustment Decision in Figure 2. The decisions are sent to Transmitter as Adjustment Command on a feedback path.

3.3 The Quality Measure

The Quality Measure plays an important part in statistical radio link quality control. This metric has to be closely related to the QoS delivered by the RX Bits. In addition, it should be possible to measure this metric in real-time. An example of Quality Measure is the bit error probability (BEP). This measure is adopted for the remaining of this document and can be estimated from the log likelihood ratios (LLR) of a soft-decision decoder, which is a common feature of the modern wireless standards.

Let λ_i denote the LLR for the i-th bit in sequence of decoded bits (RX Bits). By definition, λ_i represents the likelihood that the decoded bit is correct. Therefore, the probability of error BEP, denoted here as ε_i, for the decoded bit, is calculated according to [2].

$$\varepsilon_i = \frac{1}{1+e^{|\lambda_i|}} \tag{1}$$

Equation (1) provides a simple and elegant way for calculating the radio link quality based on information that is already available at the receiver, i.e. the decoder LLR. The density function $f(\varepsilon_i)$ representing the underlying statistical model governing variations of ε_i in an AWGN channel has been given in [2].

$$f(\varepsilon_i) = \frac{1}{4\sqrt{\pi\gamma}} \cdot \frac{1}{\varepsilon_i(1-\varepsilon_i)} \left\{ \begin{array}{l} \exp\left[-\frac{(\ln(1/\varepsilon_i - 1)+4\gamma)^2}{16\gamma}\right] \\ +\exp\left[-\frac{(\ln(1/\varepsilon_i - 1)-4\gamma)^2}{16\gamma}\right] \end{array} \right\} \tag{2}$$

for $0 \leq \varepsilon_i \leq 0.5$. The functional block diagram showing how the link quality BEP is derived from the received signal RX Signal is depicted in Figure 3. Here, the received symbols are decoded by a soft-decision algorithm represented by the function block Decoder to deliver the output bits (RX Bits). Subsequently, the block Quality Measure calculates BEP from the log-likelihood ratios LLR, which is a byproduct of the soft-decision algorithm in Decoder.

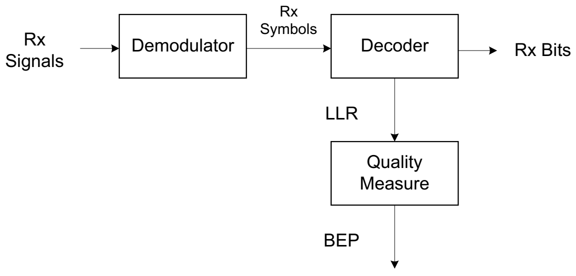

Figure 4: Measuring Link Quality

3.4 Adaptation Rules

With reference to Figure 3, the Quality Measure ε_i is used as the input to the Adjustment Decision function of the SRLQC scheme. The Adjustment Decision implements the functions of monitoring the stationarity of the Quality Measure, and making appropriate decisions based on the outcome of monitoring according to the following rules:

1. Link is stationary: make no adjustment (R1)

2. Link is approaching non-stationarity: make a minor adjustment (R2)
3. Link is already non-stationary: make a major adjustment or possibly disconnect (R3)

The three rules above constitute the link adaptation policies of SRLQC. Rule R1 states that the radio link quality is satisfactory and no changes to the current link parameters are necessary. Rule R2 is applied when the quality is still adequate but there are signs that it is approaching non-stationary. This could mean that the quality is becoming much better than required or it is approaching its limit of becoming unacceptably poor. This scenario is highly likely in a time-varying radio channel and it is possible that rule R2 has to be carried out quite often. In this case, a minor adjustment can be applied to the link. This can be done, for example, by adjusting the transmitter power up or down in small increments. It enables adaptation in a fast and efficient way.

The link adaptation policy presented by R2 allows only for small link quality adjustments within a given ACM scheme. More severe scenarios, whereby link quality cannot be handled by merely applying small adjustments, require major changes to the link. Rule R3 embodies the link adaptation policy for such scenarios. In this case, a major adjustment is applied to the link parameters. For example, a different ACM scheme is adopted for the signal transmission. The selection of ACM scheme should allow the highest possible modulation order while satisfying the link quality requirements. Progressively more robust ACM schemes are selected as the link quality deteriorates. Conversely, as the link quality improves ACM schemes with increasingly higher throughput are selected. Although it is possible in the implementation of R3 to allow jumps between any two permissible schemes within the ACM set, the channel does not change so abruptly to necessitate that. In practice, the next higher or lower ACM scheme to the current one is chosen. In the event that the most robust ACM is already in use and the quality requirement is not met the link can be disconnected.

3.5 Integrated Monitoring and Adjustment

The Adjustment Decision embodies a SPC algorithm for monitoring the stationarity of Quality Measure. The timely application of the adjustment rules and consequently the performance of the SRLQC scheme depend on this SPC algorithm. Several algorithms available can be adopted for SRLQC. These include the Shewhart chart, exponentially weighted moving average (EWMA), and the cumulative sum (cusum) scheme [1]. Although any one of the SPC monitoring schemes can be incorporated for SRLQC, the approach based on the cusum scheme is further discussed in this paper. The cusum scheme is particularly powerful and sensitive for detecting small deviations in the pdf of the process that is being controlled.

A so-called two-sided cusum scheme can be used for monitoring that the link quality. The upper and lower cusums Q_i^H and Q_i^L are calculated per observed ?i according to the following recursive expressions:

$$Q_i^H = \max(0, \varepsilon_i - T + Q_{i-1}^H) \tag{3}$$

and

$$Q_i^L = \max(0, \varepsilon_i - T + Q_{i-1}^L) \tag{4}$$

where T is the so-called target value for ε_i. For radio links, T is in effect a target bit error rate (BER. Q_i^H is used for monitoring an increase in the BEP (a degradation in the link quality), and Q_i^L is used for monitoring the reverse situation i.e. an improvement in the link quality. The initial values of Q_i^H and Q_i^L can be zero. However, optimal values for the initialization of the algorithm can be calculated which lead to faster detection speeds. The cusum metrics represented by Equations 3 and 4 in essence measure the accumulated deviation of ε_i from its target value T over a measurement interval. When the link quality is under control, the deviations of ε_i on both sides of the target are on average cancel out and, therefore, Q_i^H and Q_i^L stay near zero. It is possible to observe a consecutive run of ε_i values, which fall on the same side of the target value. In this case, Q_i^H (or Q_i^L) can increase (decrease) depending on the observed run length. Generally, values further away from zero become increasingly less likely as that would require longer run lengths of ε_i on the same side of the target. The run lengths of ε_i occur with probabilities that can be determined from the pdf $f(\varepsilon_i)$. Therefore, given $f(\varepsilon_i)$, it is possible to calculate warning and action limits for cusum variables Q_i^H and Q_i^L.

The SRLQC algorithm for Adjustment Decision is summarized in Algorithm 3.1. Here r_L and r_H denote the warning limits for the lower and upper cusums, respectively, and h_L and h_H denote the corresponding action limits for Q_i^H and Q_i^L, respectively.

4 Expected Performance

The performance of the SRLQC scheme can be measured in terms of range of tolerable link quality variation, the delay in detection of a change in $f(\varepsilon_i)$, and the probability of false alarm. The detection delay is the average number of samples (run length) of ε_i that are observed since a change in $f(\varepsilon_i)$ occurs until the change is detected by Q_i^H or Q_i^L crossing a warning or action limit. The probability of false alarm refers to the non-zero probability that Q_i^H or Q_i^L can cross a warning or action limit even if $f(\varepsilon_i)$ remains unchanged. There is an underlying interrelationship among these performance measures, which necessitates careful design of

Algorithm 3.1 SRLQC Adjustment Decisions

```
if $Q_i^H < r_H \wedge Q_i^L > r_L$ then
    Apply R2: Do Nothing
else if $Q_i^L < r_L$ then
    if $Q_i^H > h_H$ then
        Apply R2: Request lower Tx Power
    else
        Apply R3: Request Higher AMC
    end if
else if $Q_i^H > r_H$ then
    if $Q_i^H < h_H$ then
        Apply R2: Request higher Tx Power
    else
        Apply R3: Request Lower AMC
    end if
end if
```

algorithm parameters T, r_L, r_H, h_L and h_H. For example, the detection delay cannot be decreased without increasing the probability of false alarm or decreasing the allowable range of quality variation.

5 Implications for CQI in LTE

An extensive set of signaling options enable a variety of ways in which CQI can be signaled between a User Equipment (UE) and a base-station. They range from the simple to highly complex (flexible).

5.1 Remembering HSPA

In the terminology of the 3rd Generation Partnership Program (3GPP), The High-Speed Packet Access (HSPA) is a predecessor of the Long-Term Evolution (LTE). The former is also known as Release 7 and the latter as Release 8. In HSPA, issues relating to CQI were simpler. Here, an uplink control channel (called the High-Speed Dedicated Physical Control Channel HS-DPCCH) allowed room for UE to send its CQI to Node B (NB). The CQI was used in NB to select the right transport format. Specifically, a 5-bit CQI field was error protected by a (20,5) code and joined a 10-bit Hybrid ARQ field to make up the HS-DPCCH, as shown in Figure 5.

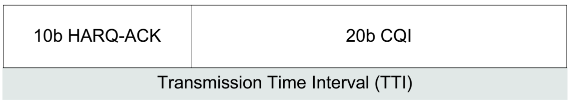

Figure 5: CQI Field in HSPA HS-DPCCH

5.2 CQI in LTE

In LTE, mechanisms for CQI feedback from UE to the evolved NB (eNB) can be similar, or can be much more flexible [3]. It is still possible to send (for a single antenna), the CQI as a 5-bit index into a table of 32 different the modulation and coding schemes. Yet, LTE allows for a variety of alternative CQI schemes [4]. Periodic CQI reports can be carried on the PUCCH (Physical Uplink Control Channel) when the UE is not scheduled for transmission. Otherwise, a scheduled UE can send its CQI over PUSCH (Physical Uplink Control channel). On-demand, non-periodic, reports are also possible in LTE and are only carried on the PUSCH. The CQI reports over PUCCH can be decoded by eNB instantly. To reduce overhead, the PUCCH must carry much less bits than the PUSCH, whereas the CQI reports over PUSCH must be decoded from several transmissions. So a trade-off exists between how much information can be fed back at the expense of delay in retrieving the feedback CQI bits. A number of options exist for CQI reporting over both PUCCH and PUSCH including UE-assisted sub-band selection and periodic reporting of different CQI types. When compared to the single CQI report of HSDPA, LTE has considerably more sophisticated reporting structure with the potential for increased performance. All these options aim to increase the performance of the system and many reflect differing views from 3GPP contributors on how CQI feedback ought to be specified or implemented. They have two things thing in common. First, they leave it up to implementers to decide how to use the CQI reporting schemes. Although is approach turns out to be the right compromise, it also indicates the absence (at least in the public domain) of a unified framework. The compatibility and interoperation of different implementations remain a major challenge for the mobile operators who decide to deploy LTE. Second, LTE standards do not specify the CQI measurement scheme. This is also up to implementers and/or operators.

5.3 From SRLQC to CQI in LTE

From Figure 3 is not hard to recognize CQI as the Adjustment Command. In Algorithm 3.1 we only have three rules, and we covered both power and rate control (through AMC modes), which are intricately related. The key point here is that SRLQC can lead to Adjustment Decisions that fit into only a few bits. With the simplest case of 5-bit CQI (available in both HSPA and LTE), we can have 32 rules. For rate (or power adaptation), we believe 32 levels may turn out to be too much. For packet scheduling, which is another major application of CQI, further investigations are necessary.

6 Conclusions

In this paper, we described measurement techniques that can used to calculate CQI. We made no assumption about channel models. Instead, we focused on simple ways of detecting when the link goes out of control and outlined an algorithm to adjust power or modulation/coding mode to bring the link back under control.

Overall, a new framework for the measurement and adjustment of radio link quality was described with the following features.

- The use of SPC, which is well-suited for monitoring and control of random process. Additionally, SPC provides powerful and well-established statistical tools for achieving its goals.
- Our approach does not require the model of time-varying radio channel to be known.
- It does not require an accurate mapping between the channel SNR and the receiver BER.
- It does not make adjustments to the transmitted signal for every received signal sample. Adjustments are only necessary when the warning or action levels are crossed.
- The Quality Measure is an excellent representative of the QoS of the application.
- The Quality Measure can be readily calculated from the soft-decision decoder LLR values.

To the best of our knowledge, the use of SPC for radio link quality control has not been widely reported. For this reason, we believe that although SPC itself is not new, its use for radio link quality monitoring and adjustment is novel. Within the context of LTE, this paper provided a simple way for measuring link quality and discussed how these measurements can be mapped to parameters suitable for CQI signaling and feedback.

References

[1] G. Box and A. Luceno, Statistical Control by Monitoring and Feedback Adjustment, Wiley Interscience, 1997.

[2] B. Rohani and K. Homayounfar, Computation of Instantaneous Bit Error Probability from Log-Likelihood Ratio, RCS2008-150 pp.119-123.

[3] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding,(Release 8), 3GPP TS 36.212 V8.3.0 (2008-05).

[4] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures,(Release 8), 3GPP TS 36.213 V8.5.0 (2008-12)