Link-to-System Level Interfaces for the Study of Radio Resource Management Techniques: Link Adaptation, a Case Study

Invited Paper

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Abstract- **Link Adaptation is an adaptive radio link technique that selects a transport mode, from a set of predefined modes of varying robustness, depending on the channel quality conditions and dynamics. Since the operation of Link Adaptation algorithms is based on channel quality estimates, it is important to analyse its performance with link level models that properly capture the channel conditions and dynamics. In this context, this paper investigates the effect that different link-to-system level interfaces have on the predicted performance and decisions regarding the optimum configuration of Link Adaptation algorithms.**

I. INTRODUCTION

The steady increase in demand for traditional voice services and the introduction of new bandwidth-consuming data services is creating new challenges for mobile operators that need to implement the means to efficiently use the scarce available radio resources. The efficient and dynamic use of the radio resources, which is a key aspect of research conducted for 3G and future mobile systems [1], is the main aim of Radio Resource Management (RRM) techniques. One of these RRM techniques is Link Adaptation.

Link Adaptation (LA), initially developed as a 3G technique, has been identified as a key technology for evolved GSM systems such as the Adaptive Multi-Rate codec (AMR), General Packet Radio Services (GPRS) and Enhanced Data rates for GSM Evolution (EDGE). The potential and benefits of LA are such that it is being considered for the High-Speed Downlink Packet Access (HSDPA) system, which represents the future evolution of 3G systems. The basis of LA is to assess the channel conditions and then use a transport mode, from a set of predefined options, that is optimised for these conditions according to a predefined criteria.

The performance evaluation of a cellular system is usually conducted at two different levels: link level and system level. While the former models the radio link at the bit level, the later models a mobile radio network. Interfaces between these levels are then necessary to analyse the overall performance.

Different levels of accuracy in the representation of transmission errors and in the representation of the inherent variability present in the radio channel can be targeted with such interfaces, depending on the particular study carried out at the system level. System level studies, including many concerning the performance of LA algorithms (e.g. [2]), are usually based on simple link-to-system level interfaces that model errors at the block level and do not include fast fading at the system level. Different studies (e.g. [3], [4] and [5]) have proposed new link-to-system level interfaces that improve the accuracy in the representation of the link level behaviour.

Since the variability present in the radio channel is an important element for the operation of adaptive radio link techniques, the aim of this investigation is to assess the impact that link-to-system level interfaces have on the study of these techniques and in particular of LA. For this purpose, two link-to-system level interfaces, each with different degrees of accuracy, have been implemented in the context of this work. Of particular importance in this study are the predicted performance of LA algorithms and decisions regarding its operation and optimum configuration to maximize system performance.

II. GPRS RADIO INTERFACE

This study has been conducted for packet data transmissions in a GPRS-like system. The GPRS radio interface can be modelled as a hierarchy of logical layers with specific functions [6]. This work focuses on the RLC/MAC and physical layers. While the Medium Access Control (MAC) sublayer defines the procedures enabling multiple users to share a common transmission medium, the Radio Link Control (RLC) sublayer is in charge of backward error correction of erroneously delivered RLC blocks by means of a selective retransmission mechanism. The physical layer is responsible for data unit framing, data coding and the detection and correction of transmission errors by means of a Forward Error Correction mechanism.

Prior to transmission, data packets are segmented into smaller data blocks across the different layers, with the final logical unit being the RLC block. The resulting RLC data blocks are then coded and block-interleaved over four normal bursts in consecutive TDMA frames. Four channel coding schemes, CS1 to CS4, are specified for the GPRS packet data traffic channels. Each scheme has been designed to provide different resilience to propagation errors under unfavourable radio conditions. As an RLC block has a fixed length of 456 bits, the different error correction capabilities of each coding scheme makes the payload transmitted in an RLC block dependant on the coding scheme used. Therefore, the different coding schemes offer a trade-off between throughput and coding protection, paving the way for the application of Link Adaptation to GPRS. The characteristics of the different coding schemes are summarised in Table 1.

Although the current GPRS standard does not contemplate CS changes for retransmissions, it has been considered here so that results are not conditioned by GPRS limitations.

TABLE I
GPRS CODING SCHEMES CHARACTERISTICS

Scheme	Code rate	Payload	Data rate (kbits/s)
CS1	1/2	181	9.05
CS2	≈2/3	268	13.4
CS3	≈3/4	312	15.6
CS4	1	428	21.4

III. SIMULATION ENVIRONMENT

In order to evaluate the impact of different link-to-system level interfaces on the performance evaluation of adaptive radio link techniques such as Link Adaptation, link and system level simulation tools have been developed.

A. Link Level Simulation Tool

A high-speed link level simulation tool [7] has been implemented in order to produce different link-to-system level interfaces. This tool is an evolved software version of a real-time hardware emulator initially designed to demonstrate the effectiveness of LA for circuit-switched voice communications, based on the GSM standard, in a dynamically varying radio environment [8]. A key aspect of this emulator is its modular design, allowing for further extensions of the tool to model systems such as GPRS, AMR or EDGE. In such context, the emulator has been extended for an initial link level assessment of GPRS and, subsequently, to produce the different link-to-system level interfaces necessary, for this work, and for an accurate prediction of the performance and operation of adaptive radio link techniques.

The link level tool, illustrated in Figure 1, models the full GPRS transmission chain by means of a C++ simulator that implements the GPRS coding schemes and models the radio transmission errors by means of a database of error patterns. These error patterns were previously obtained with the bit level simulation package COSSAP. All four GPRS coding schemes have been implemented in the simulator. When simulating the physical layer, the channel coding output is first interleaved and then the radio propagation effects are added. The output of this sum is then de-interleaved before being passed to the channel decoding process. However, de-interleaving the error patterns and adding them to the channel coding output is equivalent. This last solution has been adopted for the sake of simplicity.

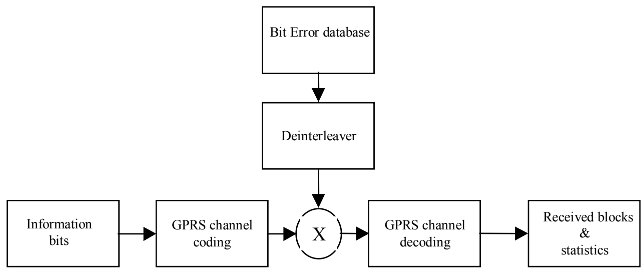

Fig. 1. GPRS link level simulator

The main benefit of the link level simulation approach considered in this work is the significant reduction in simulation time obtained once the error patterns have been produced. This benefit is actually obtained without reducing the accuracy of the radio link quality representation [7].

The link level simulations have been conducted for typical urban and rural channel scenarios (using channel models following the recommendations proposed in [9]), various mobile speeds (5km/h, 50km/h and 250km/h) and single and multislot scenarios [10]. The simulations have been done under an interference-limited environment following ETSI recommendations [9]. The results presented in this work will focus on the single slot urban scenario and a mobile speed of 50km/h.

B. System Level Simulation Tool

In order to ensure high accuracy and to account for sudden channel quality variations, an event-driven simulator working at the burst level has been implemented for the system level study. This tool represents the dynamic behaviour of the channel quality in terms of the Carrier to Interference Ratio (CIR).

The simulator models a sectorised macrocellular network and concentrates on the downlink performance. The system load is varied by changing the number of users in the system, with each user operating for the complete duration of the simulation. Users are assigned channels in a first-come-first-served basis and the channel is kept until all its data has been correctly transmitted. Following the study presented in [11], a single slot allocation strategy has been implemented by means of a random allocation scheme. Although mobility has been implemented, handover between sectors has not been considered. The boundary effects have been removed by using a wrap-around technique.

Power Control (PC) or Slow Frequency Hopping (SFH) mechanisms have not been implemented in the results reported. PC and SFH directly affect the operation of LA and therefore the use of both techniques together with LA would require the definition of an algorithm describing how they should interact. Since the definition of such algorithm is out of scope of this work, PC and SFH have not been considered here.

Two different traffic sources have been implemented, WWW browsing and email, with the traffic type evenly distributed among users at 50%. No channel partition has been applied between the two services and results are collected individually for each type of traffic from the central cell. Both traffic sources have been implemented as an ON/OFF model. For both traffic models, the transmission of a new packet cannot start until the previous transmission has finished, i.e. all the data has been correctly received. The active transmission time will hence depend on the link quality conditions. Since the work considers non real-time data services that require a highly reliable transmission, an Automatic Repeat reQuest (ARQ) protocol has been implemented to request the retransmission of erroneous blocks; the protocol has been implemented following the GPRS specifications. More details on the traffic sources can be found in [12].

The main simulation parameters employed are summarised in Table 2.

IV. LINK-TO-SYSTEM LEVEL INTERFACES

As previously mentioned, the study of a cellular system is usually performed at two different levels: system and link level. The reason for this separation is the high computational requirements generally associated with the link level analysis. Usual procedures to interface both levels are to use the link level analysis as a source of information for the system level. In particular, the effects at the physical layer are generally included by means of a set of Look-Up Tables (LUTs) mapping the CIR to a given link quality parameter such as the Block Error Rate (BLER); this modelling approach reduces the complexity of system level simulations. Different LUTs need to be produced for different operating conditions and different levels of accuracy can be targeted with the LUTs depending on the particular study carried out at the system level. This section presents two different approaches implemented in this work to interface the link and system levels. Each interface provides a different degree of accuracy in the representation of the variability present in the radio environment.

TABLE II
SIMULATION PARAMETERS

Parameter	*Value*
Cluster size	4
Cell radius	1km
Sectorisation	120º
Modelled interference	1st and 2nd co-channel tiers
Nº of modelled cells (wrap-around)	25
Slots per sector	16
Pathloss model	Okumura-Hata. Although this model was based on measurements done for distances greater than 1km, it can be extended for distances below 1km [13].
Shadowing	Log-normal distribution 6dB standard deviation and a 20m decorrelation distance
Vehicular speed	50km/h
WWW main characteristics	Components modelled: number of files per web page, file sizes, active OFF times and inactive off times.
Email main characteristics	Email size distribution is bimodal (emails with or without attachments)
ARQ protocol	Assumed perfect feedback of ARQ report and no RLC block losses
ARQ window size	64 RLC blocks
ARQ report polling period	16 RLC blocks

The first approach, generally used in the literature, maps the mean CIR experienced over the four bursts used to transmit a RLC block to the final block quality measure, i.e. BLER. Effectively this approach only models the behaviour at the RLC block level and will therefore be referred in the rest of this paper as block level modelling.

The combined effects of convolutional coding and interleaving make the block errors dependent not only on the mean block quality but also on the quality distribution among the four bursts used to transmit an RLC block. In order to improve the modelling accuracy and the representation of the variability present in the radio channel, a more sophisticated approach, which models the behaviour at the burst level, has also been implemented. This second approach, that will be referred in the rest of this paper as burst level modeling, was proposed in the European ATDMA project [3]. A similar modeling approach was later proposed for GSM [4].

The burst level interface is composed of two sets of LUTs. The interface requires as input from the system level the mean CIR experienced in a given burst. This mean CIR value takes into account the pathloss, shadowing and interference relationships in the system. The first interface (LUT-1) extracts the burst link quality, represented by means of the Bit Error Rate (BER), for the measured burst CIR. As illustrated in Figure 2, this interface is represented as a cumulative distribution function (cdf) of the BER for a given CIR. A random process is then used to generate the actual BER from the corresponding cdf. The interest of this procedure is to model the effect of fast fading on the BER through a random process thereby including the fast fading at the system level. The BER is then estimated for the four bursts used to transmit a RLC block and a second interface (LUT-2) maps the mean BER and the standard deviation of the BER over the four bursts to a corresponding BLER value. Figure 3 shows an example of LUT-2 for CS1, a speed of 50km/h and without considering the use of frequency hopping. The BLER varies between 0 and 1. Negative values have been used to differentiate the case where the BLER is equal to 0 and the case where a given combination of a mean and standard deviation of burst quality never occurred in the link level simulations.

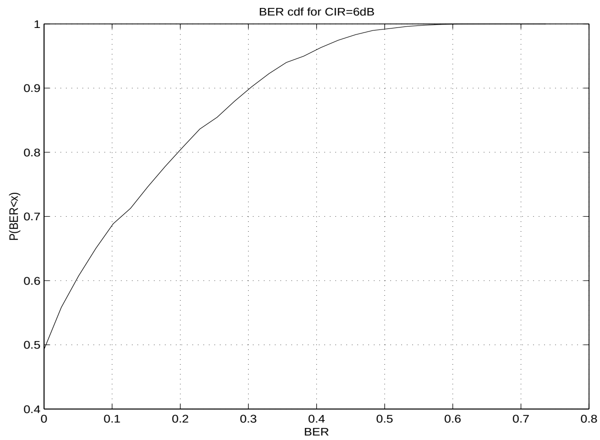

Fig. 2. Burst level modelling interface: LUT-1 (50kmh, CIR=6dB)

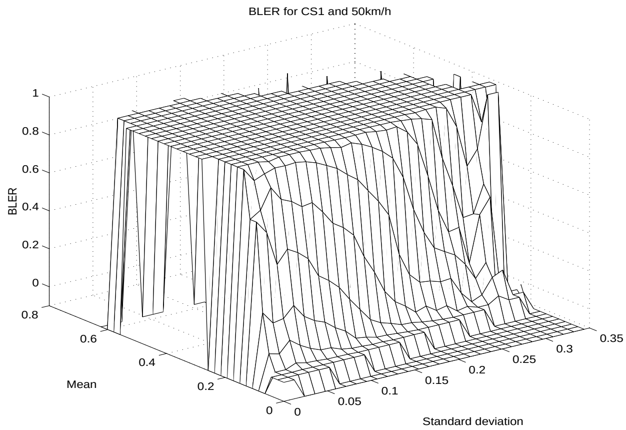

Fig. 3. Burst level modelling interface: LUT-2

V. LINK ADAPTATION ALGORITHM

The basis of LA is to assess the channel conditions and then use a CS that is optimised for these conditions, according to a predefined criteria. Since this work is based on non-real time data services, a CS is considered to be optimum if it maximises the throughput. The criterion here considered for selecting a particular coding scheme was also proposed in [14] for the study of the EDGE performance. The throughput is defined as follows:

$$Throughput = R_{CS} \times (1 - BLER_{CS}) \quad (1)$$

with R_{CS} and $BLER_{CS}$ being the data rate and BLER for a given CS.

The LA switching thresholds define the boundaries between the regions where each CS maximises the throughput. Since the throughput is defined as a function of the link level performance, i.e. BLER, the representation of these boundaries depends on the modelling approach used to represent the link level performance. If the block level modelling approach is considered, each boundary is represented by a single point corresponding to a given value of the mean CIR; see Figure 4. On the other hand, if the burst level modelling approach is considered, the throughput performance is dependent on the mean and standard deviation of the burst quality. As illustrated in Figure 5, in this case, the boundaries are defined as a collection of points, each representing a combination of mean and standard deviation of burst quality values. For both modelling approaches, no hysteresis thresholds have been implemented.

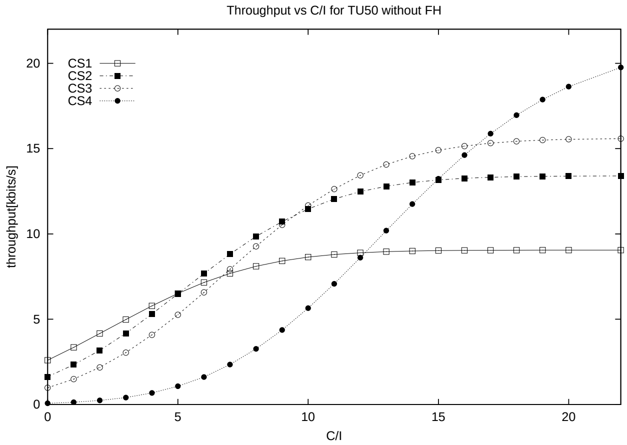

Fig. 4. Throughput performance and LA switching thresholds under the block level modelling approach

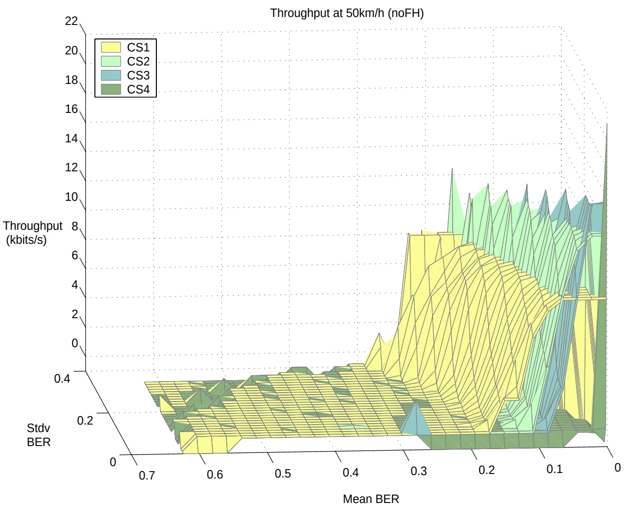

Fig. 5. Throughput performance and LA switching thresholds under the burst level modelling approach

The LA algorithm uses the quality measurements over the previous reporting period to decide on the optimum CS. The mean burst quality and the standard deviation of the burst quality over a block for each transmitted block during the last reporting period are filtered to get the quality measurements necessary for the LA algorithm. A filter with a rectangular shape has been applied throughout. In this work, a fixed initial coding scheme, CS4, has been selected at the beginning of each new data transmission.

VI. PERFORMANCE ANALYSIS

A. Performance Metrics and Evaluation Scenarios

Since the aim of the LA algorithm implemented for this work is to maximise the system throughput performance, one of the main performance metrics considered is the cdf of the throughput. The cdf of the throughput allows the assessment of the performance of an LA algorithm for the whole range of bit rates. The throughput is measured per user and is defined as the total number of bits successfully transmitted over the air interface divided by the radio transmission time. As a result, the throughput does not take into account the time a user has been waiting to get access to a channel. In this case, the throughput is measured over intervals of four seconds whenever the user is active. The throughput is collected for all users in the centre cell and the cdf of the throughput is therefore used to provide an indication of the system performance. The cdf of the throughput is also used to extract the minimum throughput for 95% of the samples, which is a frequent performance metric employed to analyse packet switched systems. Two other important performance metrics are the average number of CS changes per second requested by the LA algorithm and the cdf of the BLER. The number of CS changes per second provide an indication of the signalling load associated with the use of LA. The cdf of the BLER is also of interest since it provides an indication of the operation of the LA algorithm. The BLER values are also calculated over radio transmission intervals of four seconds. Other useful parameters to understand the functioning of an LA algorithm are the proportion of RLC blocks received with an optimal CS and the proportions of right-side and wrong-side failures. A right-side failure corresponds to the case where a user is using a non-optimal CS but one robust enough for correct reception. For the wrong-side failure, the current CS is not robust enough.

The results presented in this paper correspond to a load of 16 users per sector, which represents an average bandwidth occupancy of 45%, users receiving WWW traffic and a mobile speed of 50km/h. Four different LA updating periods have been considered: 20ms, 60ms, 100ms and 200ms. An updating period of 20ms is the shortest possible one since it corresponds to the transmission time of a single RLC block in the GPRS standard. An LA updating period defines how regularly a decision is made, by the LA algorithm, on the most suitable transport mode.

In order to ensure results with good statistical accuracy, each simulation scenario simulates the transmission of more than 30×10^6 RLC blocks in the central cell.

B. Impact of the link-to-system level interfaces on the predicted performance of the LA algorithm

The aim of this section is to evaluate the effect that link-to-system level interfaces have on the accuracy of the LA performance estimation.

Figure 6 shows the throughput performance using both link-to-system level interfaces and for a 20ms LA updating period. The results show that the prediction of the LA performance is influenced by the link-to-system level interface considered. The burst level modelling approach represents the inherent variability present in the radio channel more accurately than the block level modelling approach since it introduces the effect of fast fading at the system level. As a result, using the burst level modelling approach to interface the link and system levels provides a better indication of the true LA performance than using the block level modelling approach. In fact, Figure 6 shows that the results obtained using the block level modelling approach overestimate the predicted LA performance. For example, when considering the burst level modelling approach, the results obtained indicate that 10% of the samples have a throughput lower than 12.9kbits/s. In the case of the block level modelling approach, the maximum throughput experienced by 10% of the samples would be 14.5kbits/s. Figure 7, showing the estimated throughput performance for a 200ms LA updating period, demonstrates that these observations are not dependent on the length of the LA updating period. The higher throughput performance estimation obtained with the block level modelling approach is due to a higher proportion of blocks received with the optimal coding scheme and a lower proportion of wrong-side and right-side failures. For example, while about 78% of the RLC blocks were transmitted with the optimal coding schemes with the 20ms LA updating period and considering the burst level modelling approach, this value increased to 99% in the case of the block level modelling approach. In terms of wrong and right side failures, the values obtained considering the burst level modelling approach for both parameters was approximately 11%. However this value was reduced to below 0.5% if the simulations were conducted using the block level modelling approach for the link-to-system level interfaces. Similar observations were also obtained for the 200ms LA updating period.

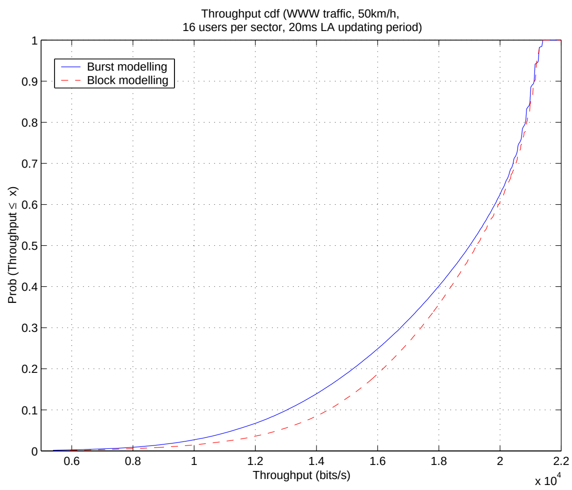

Fig. 6. Throughput cdf (20ms LA updating period)

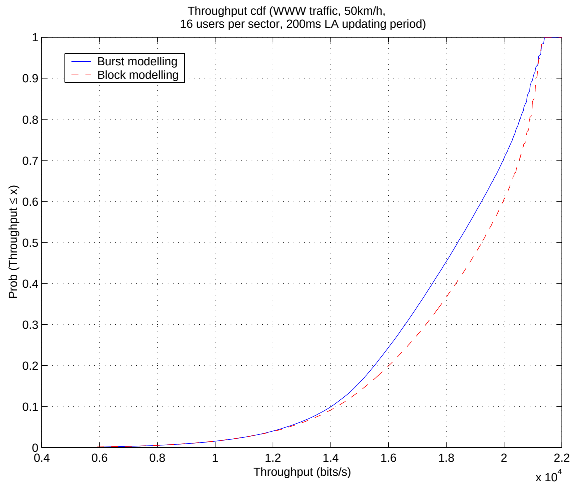

Fig. 7. Throughput cdf (200ms LA updating period)

The effect of the link-to-system level interfaces on the predicted LA performance is even more important when analysing the average number of CS changes per second. Table 3 shows the value of this parameter for both interfaces and LA updating periods of 20 and 200ms. This table clearly shows the important difference in the predicted performance depending on the interface considered. The difference is more important for the shortest LA updating period. While the predicted average number of CS changes per second with the burst level modelling approach is 10.81 for a 20ms LA updating period, the predicted value with the block level modelling approach is just 0.32. Thus, using simple link-to-system level interfaces greatly underestimates the variability present in a system and the consequent predicted signalling load associated with the use of LA. This could have a significant impact when considering the practical implementation of LA since a system designed to cope with a signalling load established according to the simulation results obtained using the block level modelling approach might not be able to cope with the signalling load present in a real system. This signalling load is better approximated considering the burst level modelling approach.

TABLE III
AVERAGE NUMBER OF CS CHANGES PER SECOND

	LA Updating Period = 20ms	LA Updating Period = 200ms
Block Level modelling approach	0.32	0.275
Burst Level modelling approach	10.81	1.22

C. Impact of the link-to-system level interfaces on the operation and configuration of the LA algorithm

The previous section has demonstrated the importance of using appropriate link-to-system level interfaces to accurately predict the performance of LA algorithms.

Previous work [12] has analysed the configuration of LA algorithms for varying operating conditions affecting the channel quality dynamics. In particular, [12] studied the LA performance for several LA updating periods. The work presented in [12] was conducted using the burst level modelling approach. The results presented in [12] indicated that the shortest updating period (20ms, i.e. the time necessary for transmitting a RLC block) can increase the throughput to a percentage of samples but it also increases the number of samples with low bit rates. Additional results also showed that the shorter the LA updating period the higher the BLER. This last observation contradicts that obtained in [2], where the simulation results presented suggest that an improvement in the BLER performance can be obtained if using the shortest LA updating period. Although the study presented in [2] considered an EDGE system and different system parameters, it is important to note that it was conducted using the block level modelling approach for interfacing the link and system level studies. Taking into account the contradictory results obtained in [12] and [2] and the fact that both studies were conducted using different interfacing approaches, the aim of this section is to investigate whether the link-to-system level interface used may have an effect on the predicted dynamics of the LA updating periods and therefore on the decisions about how to configure the LA algorithm to maximise the system performance.

Figure 8 plots the throughput performance, using the block level modelling approach, for various LA updating periods. The results presented in this figure correspond to a load of 16 users per sector, a mobile speed of 50km/h and users receiving WWW traffic. Figure 9 also illustrates the throughput performance, and with the same operating conditions as Figure 8, but this time using the burst level modelling approach. Direct comparison of both figures shows the difference in the predicted operation of LA for various LA updating periods depending on the link-to-system level interface used. Using the block level modelling approach would predict that the LA performance is identical for the shorter LA updating periods and only slightly lower as the LA updating period increases. As shown in Figure 9, the difference in the predicted LA performance for different updating periods is much more significant with the burst level modelling approach. The main difference between the simulation results obtained with both link-to-system level interfaces is the predicted LA performance with a 20ms updating period. Considering the block level modelling approach would conclude that a 20ms LA updating period outperforms the other LA updating periods. However, the analysis conducted using the burst level modelling approach shows that, actually, the 20ms LA updating period gives the best throughput to only a percentage of the samples and it also increases the number of samples with low bit rates. Since the burst level modelling approach represents the inherent variability present in the radio channel more accurately than the block level modelling approach, using such modelling approach provides a better indication of the true LA performance and operation. The results obtained also show that the use of simple link-to-system level interfaces can lead to inappropriate decisions with respect to the optimum configuration of LA to maximise system performance.

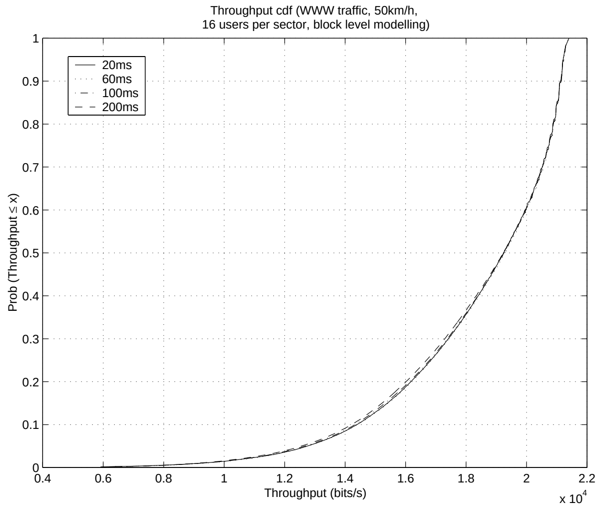

Fig. 8. Throughput cdf using the block level modelling approach

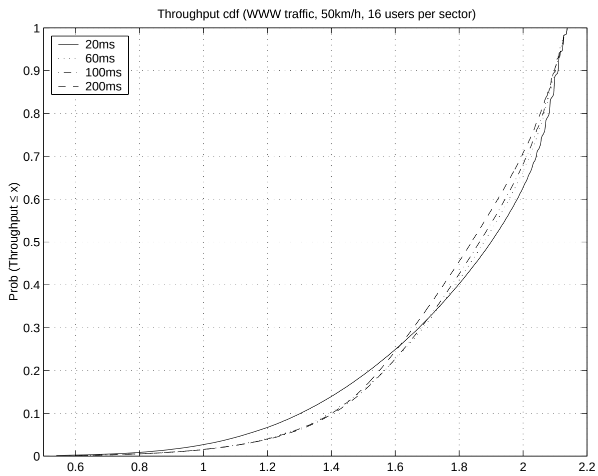

Fig. 9. Throughput cdf using the burst level modelling approach

The effect of the link-to-system level interfaces is more apparent as the BLER performance is analysed. The analysis conducted using the burst level modelling approach, and illustrated in Figure 10, showed that the BLER experienced decreases with increasing LA updating periods. On the other hand, Figure 11 indicates that if the study is conducted using the block level modelling approach, the simulation results would give the impression that the BLER actually decreases with shorter LA updating periods. It is important to note than in this case the conclusions obtained in our work would coincide with that presented in [2], where a link-to-system level interface based on the block level modelling approach is also used. These results clearly illustrate the importance of using accurate link-to-system level interfaces for extracting appropriate conclusions on the performance and configuration of LA algorithms from studies carried out by computer simulations.

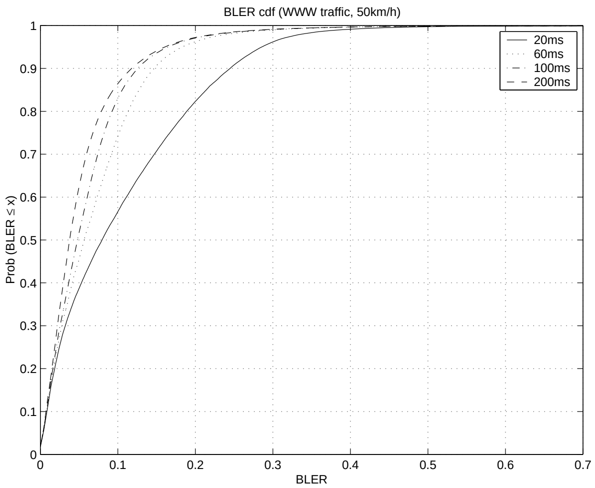

Fig. 10. BLER cdf using the burst level modelling approach

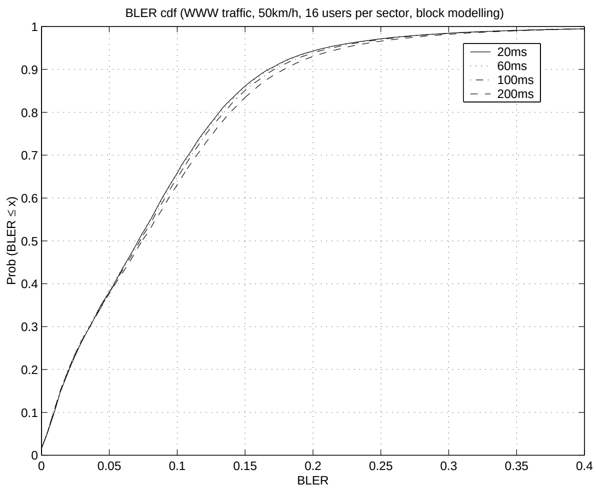

Fig. 11. BLER cdf using the block level modelling approach

VII. CONCLUSIONS

This paper has investigated the impact that different link-to-system level interfaces, each with a different degree of accuracy, have on the predicted performance and on the study of the optimum configuration of Link Adaptation algorithms in mobile radio networks.

The results obtained show that using simple link-to-system level interfaces not only fails to give an accurate prediction of the LA performance but it can also lead to the adoption of inadequate decisions about the optimum configuration of the LA algorithm in a practical system. In particular, the results presented show that the use of simple interfaces can induce an overestimation of the predicted LA throughput performance and, more importantly, derive an underestimation of the signalling load associated with the use of LA. This could have a significant impact when considering the practical implementation of LA. For instance, if a system is designed to cope with a signalling load established according to studies conducted using simple interfaces it could be the case that this system would not be able to cope with the true signalling load present in a real system. In terms of the configuration of LA algorithms, while a study conducted using simple link-to-system level interfaces would indicate that the system performance is maximised with the shortest LA updating period, the conclusions obtained using more accurate and realistic interfaces differ.

It can therefore be concluded that this investigation has highlighted the importance of using appropriate link-to-system level interfaces to not only accurately predict the performance of LA algorithms but also to take suitable decisions regarding its optimum configuration.

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