System performance and adaptive configuration of link adaptation techniques in packet-switched cellular radio networks

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Abstract

Link Adaptation is an adaptive radio resource management technique that selects a transport mode from a set of predefined modes of varying robustness, depending on the experienced channel quality conditions and dynamics. Previous work has shown the need to adapt the configuration of Link Adaptation to certain operating conditions affecting the channel quality dynamics. In particular, it was shown that the system load can considerably influence the performance and configuration of Link Adaptation techniques. The user mobile speed is another key factor influencing the channel quality dynamics. As a result, the aim of this paper is to investigate whether the user mobile speed should also be taken into account when configuring and designing the operation of Link Adaptation techniques.
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1. Introduction

The steady increase in demand for traditional voice services and the introduction of new bandwidth-demanding multimedia 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 radio resources is the main aim of

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Radio Resource Management (RRM) techniques. The definition, configuration and optimisation of RRM techniques represent a key area in the research conducted towards the development of 3G and future mobile systems [1,2].

An important RRM technique that has received considerable attention from the research community is Link Adaptation [3]. 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 [4], which represents the future evolution of 3G systems.

The basis of LA is to assess the channel conditions and then use a transport mode (e.g., modulation and/or coding scheme), from a set of possible modes, that is optimised for these conditions according to a defined criteria. The benefits obtained by applying LA compared to the case where a fixed transport mode has been used include, but are not limited to: improved speech quality [5], improved coverage [6] and increased throughput performance [7].

LA performance depends on the accuracy of the channel quality measurements and the ability of the system to adapt to channel quality variations. This ability is influenced by the LA updating period, which defines how regularly a decision is made on the most suitable transport mode. The adjustment of the LA updating period presents a trade off between number of mode changes and ability to quickly adapt to sudden channel quality variations. A LA updating period could then be considered as optimum if it maximises the performance while minimising the number of mode changes. If the channel quality presents a slow variation there is no need for a short LA updating period as it will unnecessarily increase the signalling load. Therefore, the duration of the LA updating period should be established according to the dynamics of the channel quality variation. Since these dynamics are dependent on various parameters of a mobile system, e.g., system load, the work reported in [8] investigated the optimum LA updating periods for different system loads. The analysis reported in [8] highlighted that the decision on which LA updating period to use should be based on the operating conditions and on the particular Quality of Service (QoS) strategy targeted.

Gozalvez and Dunlop [8] analysed the configuration of LA schemes under high user mobile speeds (50 km/h). Mobile speeds can also influence the dynamics of the channel quality conditions. While rapid variations of the channel quality are expected at high speeds, low speeds can produce correlated channel quality conditions over longer periods of time. As a result, the aim of this work is to analyse the dynamics of the LA updating periods for low speeds and compare the observations obtained to those presented in [8] to determine whether the configuration of LA techniques should also take into account potential variations in the user speed. An initial assessment of the potential effect of the user mobile speed on the performance of LA schemes has been reported in [9]. However, this work was conducted at the link level for the GSM system. Link level studies provide an assessment of a single communication link performance but fail to introduce system level effects, where higher-layer parameters may play a decisive role. On the other hand, system-level studies generate certain traffic and mobility patterns within a network of cells and provide an assessment of the overall system performance. In order to evaluate the system impact that user speeds may have on the performance and configuration of LA techniques, this paper conducts the investigation at the system level. In particular, the study has been conducted for packet data transmissions in a GPRS-like system.

The paper is organised as follows. Section 2 briefly summarises the main aspects of the GPRS system that affect this study. The simulation tools employed to conduct this research are detailed in Section 3. The implemented LA scheme is described in Section 4. Section 5 presents the results obtained concerning the system performance and configuration of LA for various important system parameters, in particular system load and user speed. Finally, Section 6 summarises the main contributions of this paper.

2. General packet radio service

The study reported in this paper has been conducted for packet data transmissions in a GPRS-like system. The GPRS standard can be modelled as a hierarchy of logical layers with specific functions [10]. This work focuses on the RLC/MAC and physical layers. This is due to the fact that LA, which can be considered a cross-layer RRM scheme, is an RLC/MAC technique that uses information from the physical layer to adjust its operation.

The RLC/MAC layer together with the LLC layer form the data link layer. The LLC layer provides a logical link between the mobile station and the GPRS network while the RLC/MAC layer provides services for information transfer over the physical layer. In particular, 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. As shown in Table 1, each scheme has been designed to provide different resilience to propagation errors under unfavourable radio conditions. As a result, the different coding schemes (CS) offer a trade-off between throughput and coding protection, paving the way for the application of Link Adaptation to GPRS. It is also important to note that since GPRS uses a single modulation scheme, the LA scheme considered in this investigation only considers changes of CS.

3. Simulation models

Modelling of a complete cellular radio network is usually separated into two levels: the link level and the system level. The former models the radio link at the bit level while the latter models a mobile radio network. The level separation is due to the high computational requirements generally associated with the link level analysis. Although this research concentrates on system level aspects of the LA technique, it is important to appropriately include the effects of the link level at the system level in order to provide a complete and accurate performance assessment of LA in a packet-switched cellular radio network.

3.1. System level simulator

In order to ensure high accuracy and to account for sudden channel quality variations, the system level analysis reported in this paper has been conducted by means of an event-driven simulator working at the burst level. The simulator has been implemented in C++ using the library CNCL [11]. The structure and components of the system level simulation tool are depicted in Fig. 1. The 'Cellular Environment' entity stores the location of each base station and the resources allocated at any given time by any base station. The 'Link Control' units present in the models of the base stations and mobile stations are responsible for the implementation and operation of LA.

A cellular network of equally sized three-sector macro-cells, with a cluster size equal to four, has been considered. Within the network, interference produced by first and second tier of co-channel interferers is considered. Each cell has a radius of 1 km and each sector has been assigned two carriers (i.e., 16 channels or time slots). The mobility of

Table 1
GPRS channel coding parameters

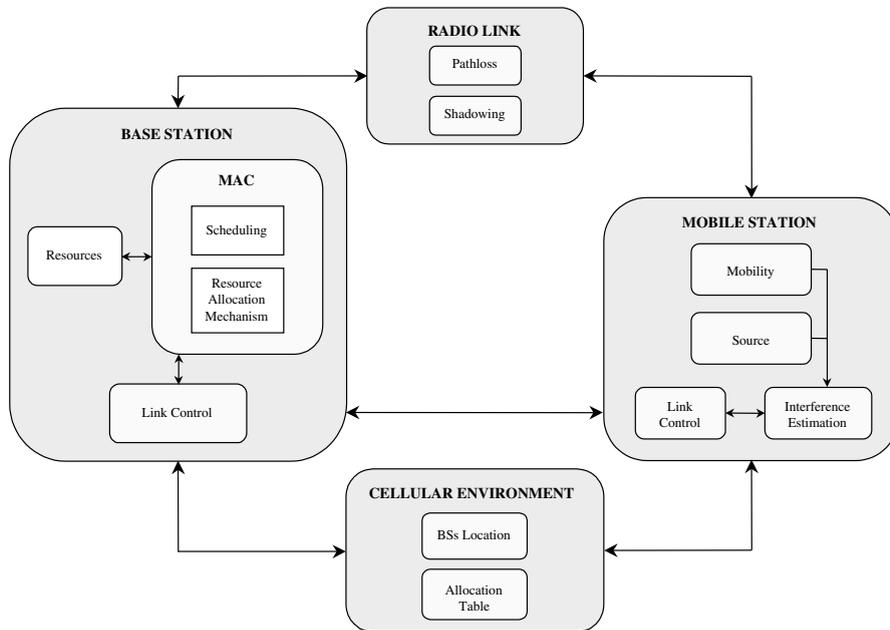| Scheme	Code rate	Payload	Data rate (kbits/s)
CS1	1/2	181	9.05
CS2	≈2/3	268	13.4
CS3	≈3/4	312	15.6
CS4	1	428	21.4

Fig. 1. System level simulation structure.

users can greatly affect the channel quality conditions. Since such conditions are the basis of the LA technique, a mobility model based on [12] has been implemented in this work. Although mobility has been contemplated, handover between sectors has not been considered. As a result, mobile stations are connected to the closest base station and not to the best serving base station. The boundary effects have been removed by using a wrap-around technique.

The simulator 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. Following the study presented in [13], a single slot allocation strategy has been implemented by means of a random allocation scheme. Users are assigned channels in a first-come-first-served basis and the channel is kept until all its data has been correctly transmitted. An ARQ protocol, following the GPRS specifications, has been implemented to request the retransmission of erroneous blocks. Perfect feedback of the ARQ report with no RLC block losses has been assumed. The ARQ window size is equal to 64 RLC blocks. An

ARQ report is sent after transmitting 16 RLC blocks [8].

Path loss is predicted using the Okumura–Hata model. Although the Okumura–Hata model was based on measurements done for distances greater than 1 km, the model can be extended for distances below 1 km [14]. The shadowing has a log normal distribution with a standard deviation of 6 dB and a decorrelation distance of 20 m. The shadowing is a spatially correlated process so that the shadowing experienced by a mobile at a given position is correlated to that experienced at a nearby position. This spatial correlation has been modelled in this work as detailed in [15]. Fast fading has also been included in the system level simulations as explained in Section 3.3. The simulator models the dynamic behaviour of the channel quality in terms of the Carrier to Interference Ratio (CIR). Power Control (PC) or Slow Frequency Hopping (SFH) mechanisms have not been implemented in the simulator. 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.

3.2. Traffic modelling

As packet-switched systems allocate channels to users only when they have some data to transmit, the traffic models employed have an impact on the pattern of channel allocations and releases. Since such allocations and releases can affect the channel quality conditions, and therefore the operation of LA, appropriate traffic models are required.

Future wireless systems will be used as a platform to support a wide range of data applications. Web browsing and e-mail are some of the most popular applications in the fix network traffic. As this trend is expected to continue on the wireless domain, Web browsing and e-mail applications have been considered in the context of this work.

The traffic type has been 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 channel quality conditions.

WWW browsing has been implemented following the model described in [16]. This model considers that a TCP connection can only transfer a single file or object. Each connection is closed after the transmission is finished and a new connection must be established for the transfer of a new file. A WWW browsing session starts with a submission of an URL request by the user. When all the requests related to that URL are complete, the user will take some time to read the information before initiating another request ('think time'). The transfer of the URL request corresponds then to the ON/active period while the users 'think time' corresponds to the OFF/inactive period. A URL request (or Web page) may contain several files and this model also characterises the number of files per Web page. An active OFF time corresponds to the time between closing a TCP connection and opening the next one to transfer a new object from the same page. The model is depicted in Fig. 2 and Table 2 summarises the distributions used to characterise the WWW traffic.

E-mail traffic has been generated following the model presented in [17]. The e-mail size has been found to be bimodal as e-mails are also used to transfer files. The cumulative distribution function of the e-mail size is defined by means of Weibull distributions

$$F(x_e) = \begin{cases} 1 - e^{-e^{-k_1 \cdot x^{c_1}}} & \text{if } F(x_e) \leqslant 0.5, \\ 1 - e^{-e^{-k_2 \cdot x^{c_2}}} & \text{if } F(x_e) > 0.5, \end{cases}$$

Table 2
Distributions and parameters for the WWW traffic model

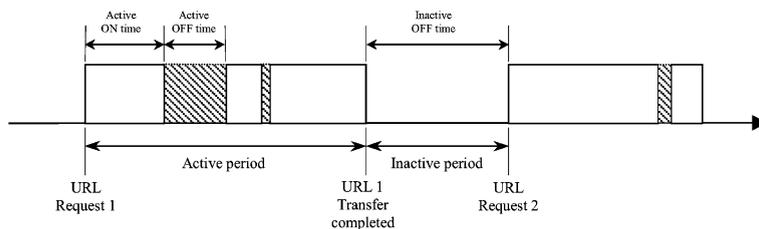| Component	Model	Pdf
File sizes	Pareto	$p(x) = \alpha k^\alpha x^{-(\alpha+1)}$ $k = 1000, \alpha = 1.0$
Active OFF times	Weibull	$p(x) = \frac{bx^{b-1}}{a^b} e^{-(x/a)^b}$ $a = 1.46, b = 0.382$
Inactive OFF times	Pareto	$p(x) = \alpha k^\alpha x^{-(\alpha+1)}$ $k = 1, \alpha = 1.5$
Number of files per web page	Pareto	$p(x) = \alpha k^\alpha x^{-(\alpha+1)}$ $k = 1, \alpha = 2.43$

Fig. 2. WWW traffic model.

where c_1 has a mean of 2.04, c_2 a mean of 0.37, k_1 a mean of 17.64 and k_2 a mean of 3.61. As for the WWW traffic model, the length of the ON period is a function of the e-mail size and the transmission rate. The OFF period is modelled as a Pareto distribution with $k = 30$ and $\alpha = 1.5$.

3.3. Link-to-system level interface

As it has been previously explained, the study of a cellular system is usually performed at two different levels: system and link level. An interface between both levels is necessary to produce a complete and final performance analysis of the particular technique under study. In order to reduce the complexity of system level simulations, 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 Look-Up Tables (LUTs). The link level

performance is then represented by a simplified model consisting of a set of LUTs mapping the CIR to a given link quality parameter such as the Block Error Rate (BLER). Different LUTs need to be produced for different operating conditions (e.g., mobile speeds and propagation environments). Also, different levels of accuracy can be targeted in the production of the LUTs depending on the particular study that is being carried out at the system level.

The work reported in [18] demonstrated the importance of using link-to-system level interfaces that accurately model the inherent variability present in the radio channel, to appropriately study the performance and configuration of adaptive RRM techniques such as LA. Following the indications provided in [18], an advanced set of LUTs has been implemented to conduct this research.

The combined effects of convolutional coding and interleaving make the RLC block errors
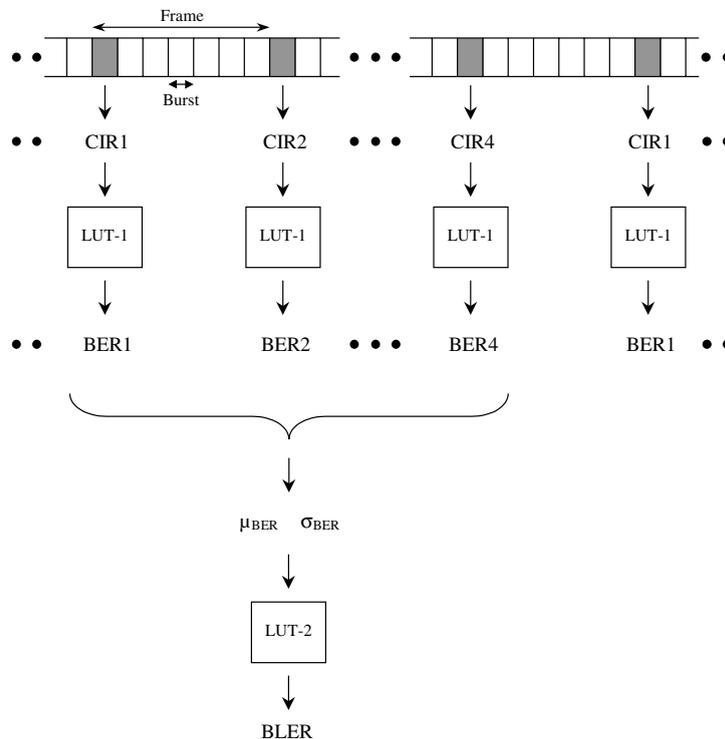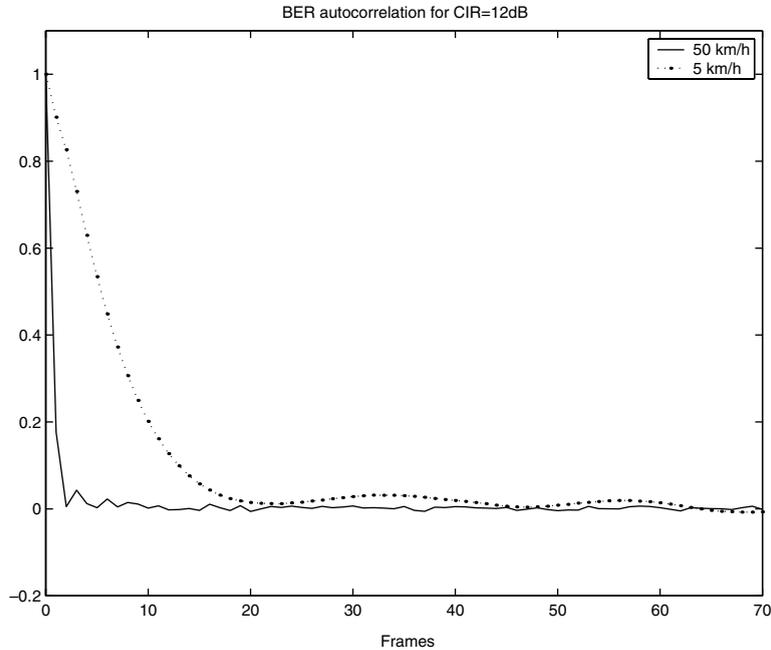

Fig. 3. Link-to-sytem level interface.

Fig. 4. BER autocorrelation for CIR = 12 dB.

dependent not only on the mean block quality but also on the quality distribution among the four bursts used to transmit an RLC block. To accurately model block errors, a link-to-system level interface working at the burst level has been implemented. This interface is composed of two sets of LUTs, as illustrated in Fig. 3. The interface requires as input from the system level the mean CIR experienced in a given burst. LUT-1 extracts the burst quality for the measured CIR. The burst quality is represented by means of the Bit Error Rate (BER). LUT-1 represents 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 purpose 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 LUT-2 maps the mean BER and the standard deviation of the BER over the four bursts to a corresponding Block Error Rate (BLER) value. The two LUTs have been produced for a typical urban (TU) environment and two mobile speeds (5 km/h and 50 km/h). The link level simulation tool used to produce the different LUTs is detailed in [19].

As it has been previously mentioned, the spatial correlation characteristic of the shadowing phenomena has been modelled in the system level simulator employed in this study. As a result, the simulator considers correlation between CIR values. However, the BER correlation that the sequence of CIR could generate is not explicitly modelled. As shown in Fig. 4, this correlation between BER values is only expected at low speeds. It is important to note that Fig. 4 illustrates the BER autocorrelation for a fixed CIR value; the level of correlation should be smaller under a variable CIR environment. Moreover, it is worth noting though, that the modelling of the CIR correlation infers an implicit characterisation of the BER behaviour, since the BER is related to the particular CIR experienced.

4. Link adaptation scheme

Wireless systems are characterised by continuous and dynamic variations of the channel quality

conditions. LA techniques have been proposed as a remedy to such channel quality variations and as a means to improve the spectral efficiency of a system. The basis of LA is to assess the channel conditions and then use a transport mode that is optimised for these conditions according to a defined criteria. If the experienced channel conditions are considered to be good then a mode with little or no error protection is selected. On the other hand, if the channel conditions are poor, a mode with extra error protection is selected. The nature of the adaptation process is predictive, since measurements of the past channel conditions are used to predict the channel conditions for the following transmission frames.

When considering the GPRS standard, the adaptation occurs at the coding scheme level. Different approaches can be taken to decide which CS is considered as optimum based on, for example, the targeted QoS for a given service. Since this work is based on data services that do not have tight transmission delays, a CS is considered to be optimum if it maximises the throughput. Other approaches could be, for example, to select the CS that minimises transmission delays or reduces the

number of blocks received in error. The criterion here considered for selecting a particular CS was also proposed in [20] for the study of the EDGE performance. The throughput is defined as follows:

$$\text{Throughput} = R_{\text{CS}} \times (1 - \text{BLER}_{\text{CS}}) \tag{1}$$

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

Based on Eq. (1) and on the representation of the BLER (an example of LUT-2 is provided in Fig. 5), Fig. 6 illustrates the throughput performance obtained with each CS as a function of the experienced channel quality conditions. Fig. 6 shows that the throughput is dependent on the mean and standard deviation of the burst quality and that each CS is optimal, in terms of throughput performance, for a given range of channel quality conditions. In particular, it is important to note the limited operating area of CS4 compared to the other CSs. Since CS4 does not have any error protection, it will only be considered as the optimum CS when transmission conditions allow no bits to be received with error.
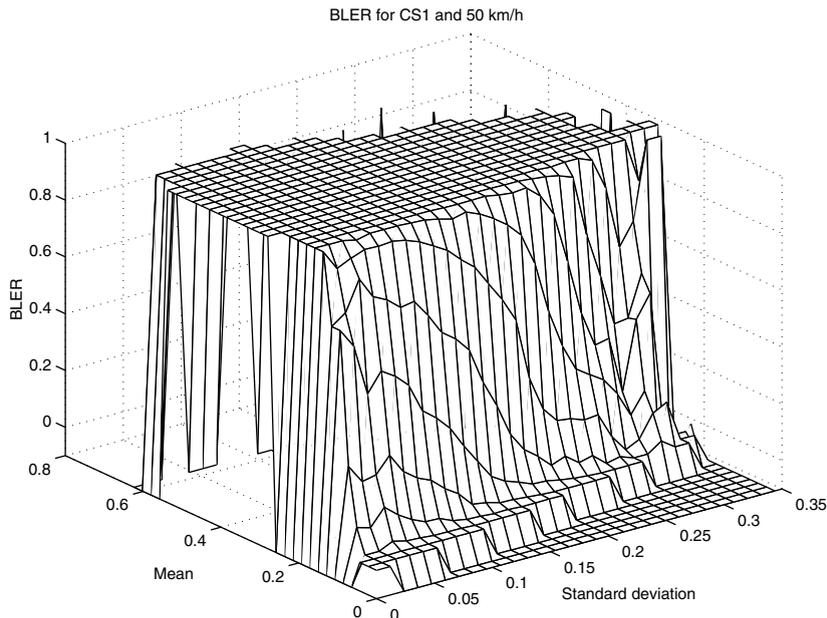

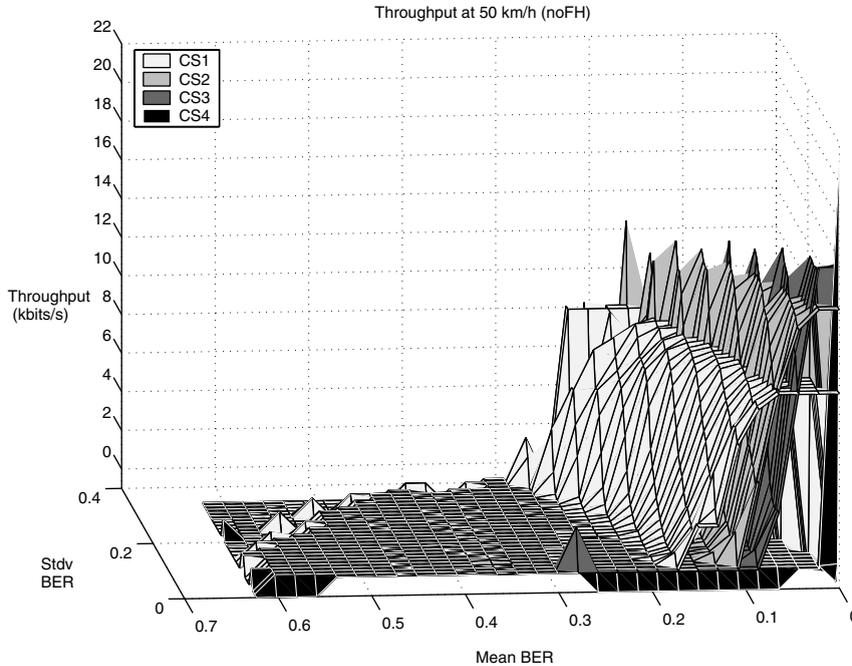Fig. 5. LUT-2: BLER vs. mean and standard deviation of BER, for CS1 at 50 km/h.

Fig. 6. Throughput performance and LA switching thresholds.

The LA switching thresholds define the boundaries between the regions where each CS maximises the throughput. For the link-to-system level interface used in this work, the boundaries are defined as a collection of points, each representing a combination of mean and standard deviation of burst quality values. For this work, no hysteresis thresholds around the boundaries have been considered.

The LA scheme uses the quality measurements over the previous LA updating period to decide on the optimum CS. The mean BER and the standard deviation of the BER over a block for each transmitted block during the last updating period are filtered to get the channel quality estimation necessary for the LA technique. A filter with a rectangular shape has been applied throughout and a fixed initial coding scheme, CS4, has been selected at the start of each new data transmission.

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

An example of the performance improvements obtained with LA is illustrated in Fig. 7. This figure plots the cumulative distribution function (cdf) of the throughput performance considering each GPRS CS and LA with an updating period of 60 ms. Fig. 7 shows that the use of LA increases the throughput performance compared to using each one of the GPRS CS. An exception to this general trend is observed for very high throughputs and when considering the use of CS4. High throughputs are obtained when very good radio link quality conditions are experienced by a mobile user. Under these conditions, CS4 is the optimal CS. If a single bit of an RLC block is detected in error, LA will change the CS to a more robust one for, at least, the next three RLC blocks; this is due to the use of a 60 ms updating period and the fact that the time to transmit an RLC block is equal to 20 ms. If no other bit errors are detected in these blocks, LA would not be using the optimal CS, i.e., CS4, for these last three blocks. As a result, its throughput performance would be slightly inferior to that obtained employing CS4.
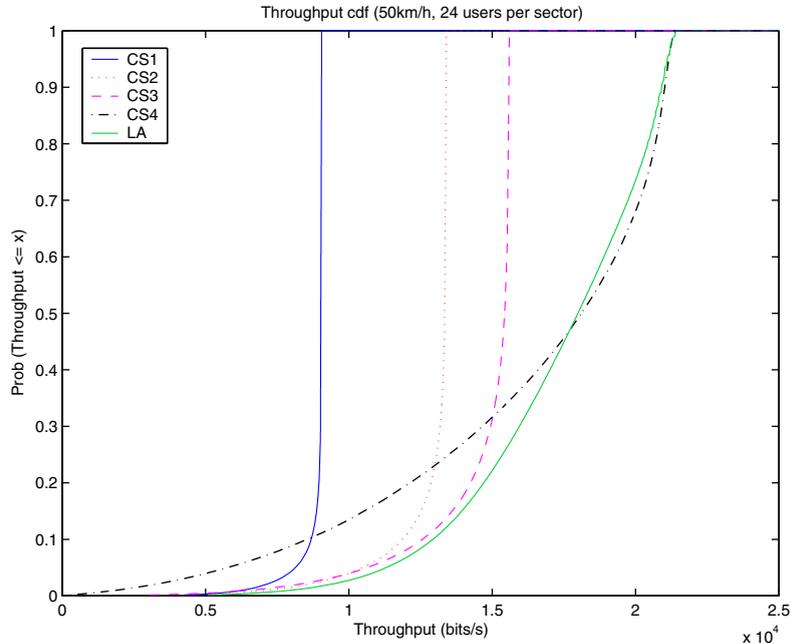
Fig. 7. Example of throughput performance for different CS and LA (24 users per sector, speed of 50 km/h, WWW and e-mail traffic).

5. Performance and configuration of LA techniques

5.1. Evaluation conditions and performance metrics

This work studies the performance and configuration of LA in packet radio networks. The performance is assessed for various user mobile speeds and system loads. In particular, this study considers speeds of 5 km/h (pedestrian environment) and 50 km/h (vehicular environment), and loads of 8, 16, 24 and 36 users per sector. These loads represent an average bandwidth occupancy of 20%, 45%, 67% and 93%, respectively. The results presented in this section correspond to those collected for only users receiving WWW traffic and mobile speeds of 5 and 50 km/h. Four different LA updating periods have been considered: 20 ms, 60 ms, 100 ms and 200 ms. Since a control loop is necessary to implement the LA algorithm, the updating period equal to 20 ms, corresponding to the shortest possible one as it is equivalent to the transmission time of a single RLC block, is considered as an ideal case.

As previously mentioned, the configuration of an LA scheme could be regarded as optimum if it maximises the performance while minimising the number of CS changes and therefore the signalling load associated with the use of LA. Since this study considers non-real time data services, the performance is assessed by means of three main parameters, namely the cdf of the throughput, the average throughput and the average number of CS changes per second. The cdf of the throughput allows the assessment of the performance of an LA scheme for the whole range of bit rates. It is also used to extract the minimum throughput for 95% of the samples, which is a general performance metric employed to analyse packet-switched systems. 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 4 s 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 average throughput is averaged over all users in the centre cell. The proportion of RLC blocks received in error, or average BLER, is also of interest since it provides an indication of the operation of LA. Another useful parameter to understand the functioning of LA is the proportion of RLC blocks received with an optimal CS. The operation of LA is also analysed by deriving the usage percentage of each CS.

In order to ensure results with good statistical accuracy, each simulation scenario (i.e., considering a different load, LA updating period and mobile speed) simulates the transmission of more than 30×10^6 RLC blocks in the central cell.

5.2. First scenario: high user mobile speeds (50 km/h)

In order to analyse whether the configuration of LA techniques should be adapted to the mobile speed, this section summarises some of the results obtained in [8] for high speeds (50 km/h).

The throughput performance for users moving at 50 km/h, considering loads of 8 and 36 users per sector and a number of LA updating periods is illustrated in Fig. 8 and Fig. 9. The results show that, for, all updating periods, the throughput performance decreases as the load increases. The increase in the proportion of blocks received in error as the load increases can be regarded as one of the main factors contributing to this behaviour; see Fig. 10.

Figs. 8 and 9 show that under every load considered, an LA updating period of 20 ms increases the number of samples with low bit rates (although only the figures corresponding to loads of 8 and 36 users per sector are shown in this section, the same trends were observed for loads of 16 and 24 users per sector). However, it can also be observed that this LA updating period gives the best throughput to a percentage of samples and that this percentage varies with the load. With 8 users per sector, this percentage is around 77%, whereas this value is reduced to around 50% when the load is increased to 36 users per sector. This is due to the fact that the proportion of blocks received in error increases
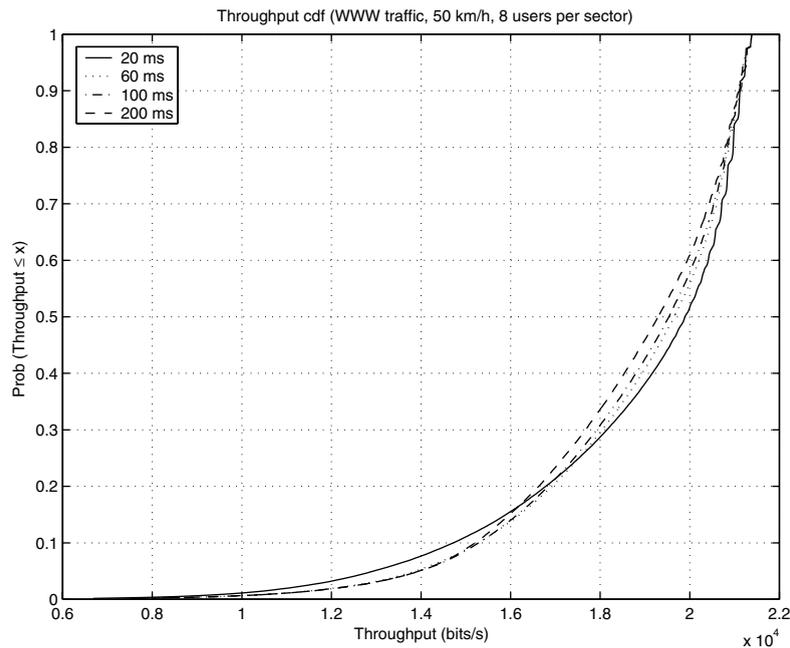

Fig. 8. Throughput cdf (eight users per sector, WWW traffic, 50 km/h).
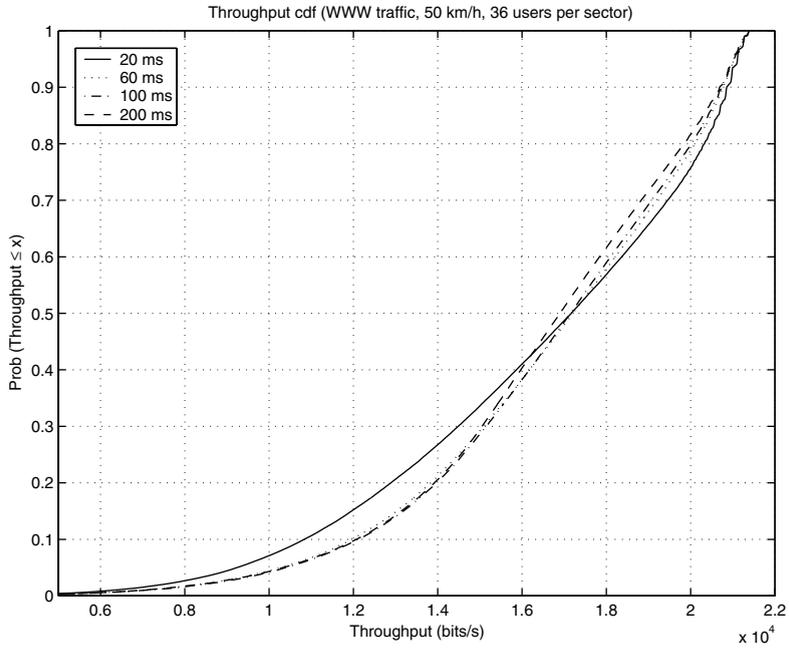
Throughput cdf (WWW traffic, 50 km/h, 36 users per sector)

Fig. 9. Throughput cdf (36 users per sector, WWW traffic, 50 km/h).

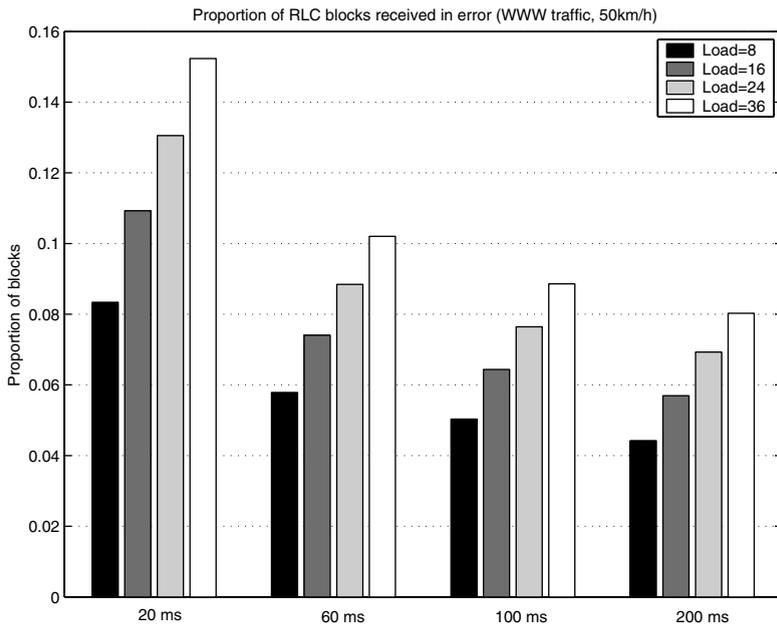Proportion of RLC blocks received in error (WWW traffic, 50km/h)

Fig. 10. Average proportion of RLC blocks received in error for various LA updating periods (WWW traffic, 50 km/h).

more notably for the 20 ms LA updating period as the load increases; see Fig. 10.

As shown in Figs. 8 and 9, the performance with LA updating periods of 60 ms, 100 ms and 200 ms is quite similar for users with low throughputs. Only for higher throughputs is there an advantage associated with using shorter LA updating periods. For these throughputs, the performance decreases as the LA updating period increases. However, as shown in Fig. 11, longer LA updating periods also reduce the average number of CS changes per sector and therefore the signalling load associated with the use of LA. The selection of the LA updating period offers then a trade-off between performance and signalling load, with varying effects under different system loads.

In terms of the average throughput, an LA updating period of 20 ms provides a poorer performance than an LA updating period of 60 ms for all loads considered; see Table 3. The difference in performance becomes more apparent with increasing loads. This is also due to the fact that, with a 20 ms LA updating period, the increase in the proportion of blocks received in error as the load augments is more significant than with the other LA updating periods. This effect also explains the fact that an LA updating period of 20 ms provides a lower average throughput than the longer LA updating period for high loads but not for the low ones. The performance is very similar, under the operating conditions considered, for LA

Table 3
Average throughput and minimum throughput for 95% of samples (kbits/s) for different updating periods and loads (50 km/h)

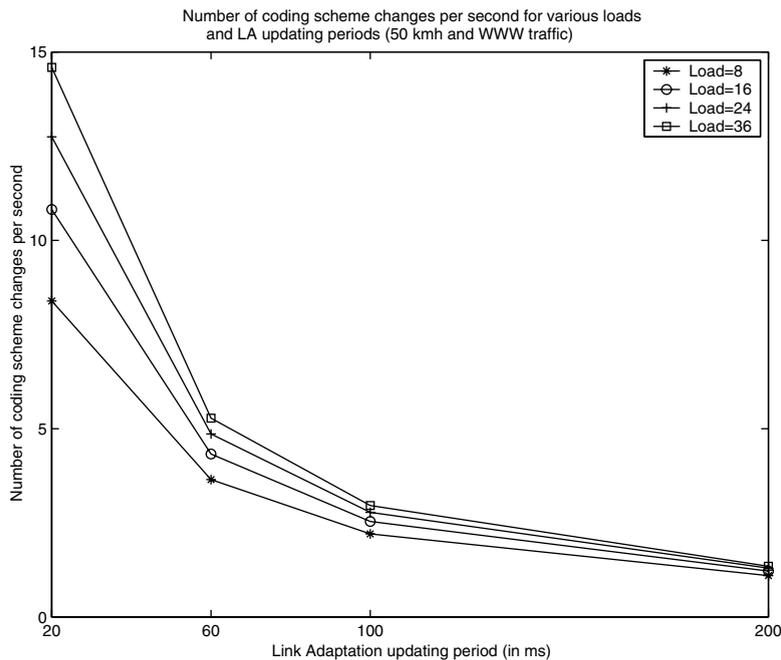| LA Up period	20 ms		60 ms	
	Avg.	Min	Avg.	Min
(a)				
Load = 8	18.81	12.95	18.83	13.87
Load = 16	17.94	11.28	18.04	12.41
Load = 24	17.21	10.24	17.36	11.28
Load = 36	16.46	9.24	16.73	10.27
(b)				
	100 ms		200 ms	
Load = 8	18.77	13.98	18.63	13.97
Load = 16	17.99	12.53	17.86	12.47
Load = 24	17.35	11.43	17.18	11.31
Load = 36	16.73	10.41	16.59	10.33

Fig. 11. Average number of CS changes per second (WWW traffic, 50 km/h).

updating periods of 60 and 100 ms, but it decreases for the 200 ms case.

The aim of a particular LA scheme implementation may be to guarantee that 95% of the samples will experience the highest possible minimum throughput. In this case, an LA updating period of 20 ms clearly underperforms the other LA updating periods for all the considered loads (see Table 3). For example, an LA updating period of 20 ms gives a throughput of greater than 11.28 kbits/s for 95% of the samples for a load of 16 users per sector. On the other hand, a LA updating period of 100 ms provides a throughput of greater than 12.53 kbits/s.

To summarise, the analysis reported in [8] suggested that, for high loads, the benefit of using a LA updating period of 20 ms is questionable. For low and medium loads, this updating period provides the best throughput for a significant number of samples but decreases the average throughput and minimum throughput for 95% of samples and increases the number of samples with low bit rates. Shorter updating periods also produce a higher number of CS changes. According to these observations, it was concluded that the decision on which updating period to use should take into account the system load and should be based on the QoS strategy targeted. That is, for example, whether the aim is to decrease the number of users with low bit rates while also decreasing the number of CS changes per second or increase the throughput to a considerable number of users.

Finally, it is important to note that similar trends and conclusions, regarding the dynamics of the LA updating periods, to that reached for the WWW traffic service were also obtained for the e-mail service.

5.3. Second scenario: low user mobile speeds (5 km/h)

The previous section has analysed the configuration of LA techniques, for different system loads, under high user mobile speeds. As illustrated in Fig. 4, mobile speeds can influence differently the channel quality dynamics. As a result, the aim of this section is to analyse the dynamics of the LA updating periods for low speeds and compare the

observations obtained to those described for high mobile speeds. The final objective of this analysis is to determine whether the configuration of LA also needs to take into account the user mobile speeds.

Fig. 12 compares the throughput performance for the two considered user mobile speeds. The results show a degradation in throughput performance, at low speeds, for transmissions with low bit rates. Fig. 12 indicates that with a speed of 50 km/h and a 200 ms LA updating period, 10% of the samples have a throughput below 12 kbits/s. This percentage is increased to over 20% for a speed of 5 km/h. As shown in Fig. 13, the degradation in performance obtained at low speeds is due to an increase in the number of blocks received in error. The lower throughput performance observed for low speeds also translates into an increase in the use of the more robust CS for low speeds compared to high speeds. Fig. 14 represents the difference in the usage percentage of each CS for a speed of 5 km/h compared to mobiles moving at 50 km/h with a load of 36 users per sector. This figure shows that using a 20 ms LA updating period derives in an increase of 105% in the usage of the most robust coding scheme, i.e., CS1, for low speeds. On the other hand, the use of the least robust coding scheme, i.e., CS4, decreases by 8% at low speeds. The same trends and observations in terms of throughput, BLER and usage percentage of the CSs have been obtained for all loads and LA updating periods considered in this study.

Figs. 15–18 show that, in terms of load variation, similar trends to the 50 km/h results described in the previous section can be observed for low speeds. However, the benefits of a 20 ms LA updating period are reduced for low speeds as the performance for high throughput transmissions under different LA updating periods gets closer. It was previously shown that, for high speeds, a 20 ms LA updating period increases the number of samples with low bit rates compared to other LA updating periods. At low speeds, a 20 ms LA updating period further increases the number of samples with low bit rates compared to the other LA updating periods.

In terms of the average throughput and minimum throughput for 95% of the samples, there
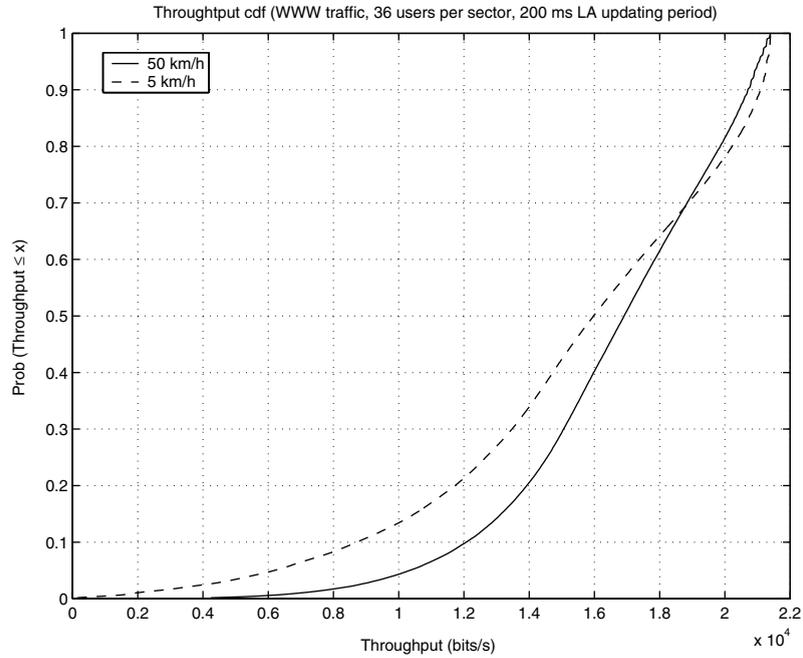
Throughtput cdf (WWW traffic, 36 users per sector, 200 ms LA updating period)

Fig. 12. Throughput cdf for a load of 36 users per sector and speeds of 5 and 50 km/h (WWW traffic, 200 ms LA updating period).
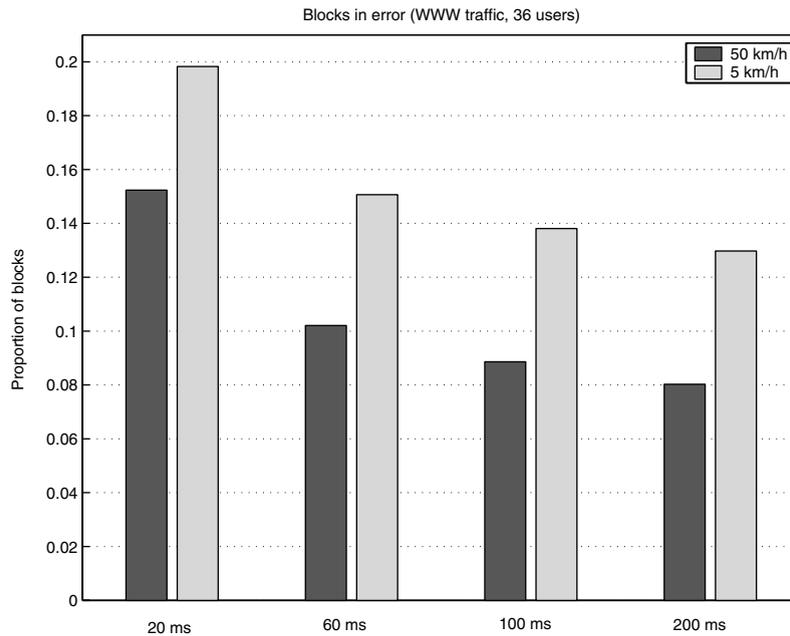
Blocks in error (WWW traffic, 36 users)

Fig. 13. Proportion of blocks received in error for speeds of 5 km/h and 50 km/h (WWW traffic, 36 users per sector, all LA updating periods).
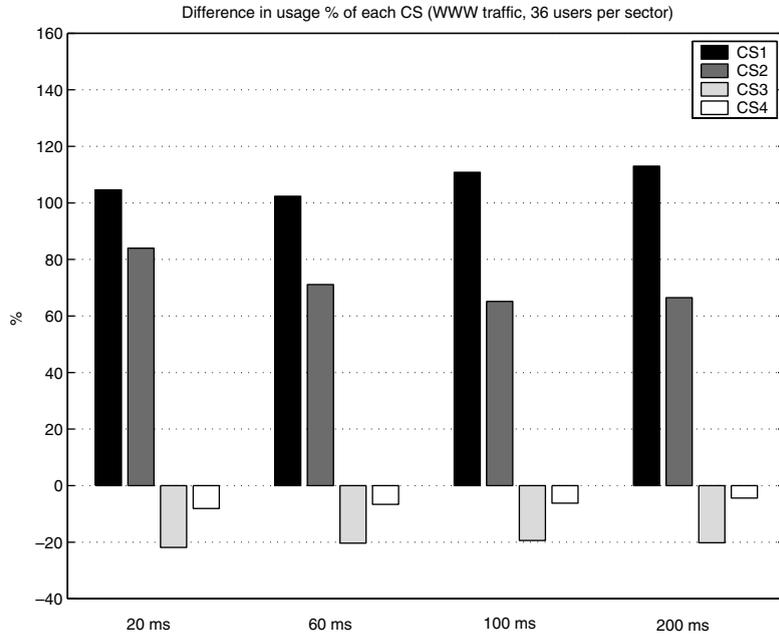
Fig. 14. Difference in the usage percentage of each CS for 5 km/h compared to 50 km/h (WWW traffic, 36 users per sector, all LA updating periods).
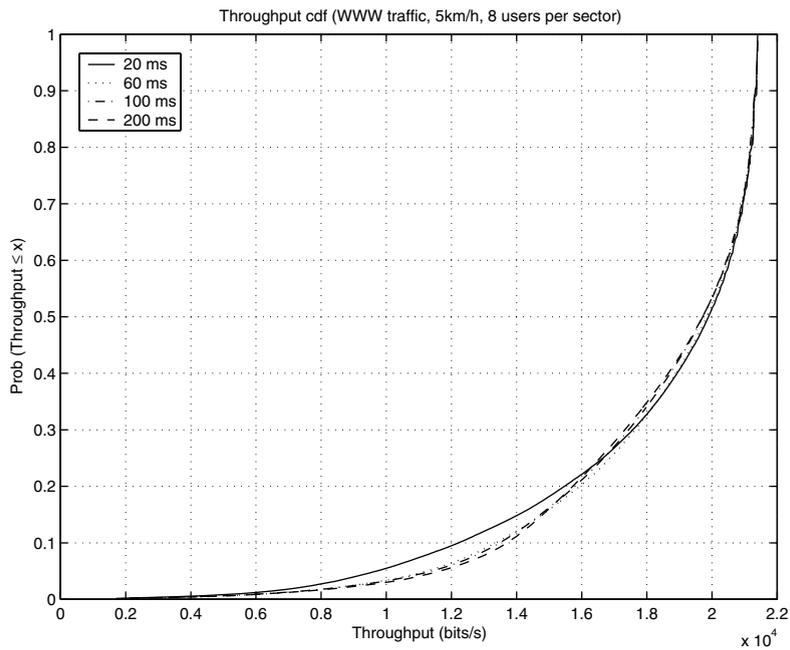

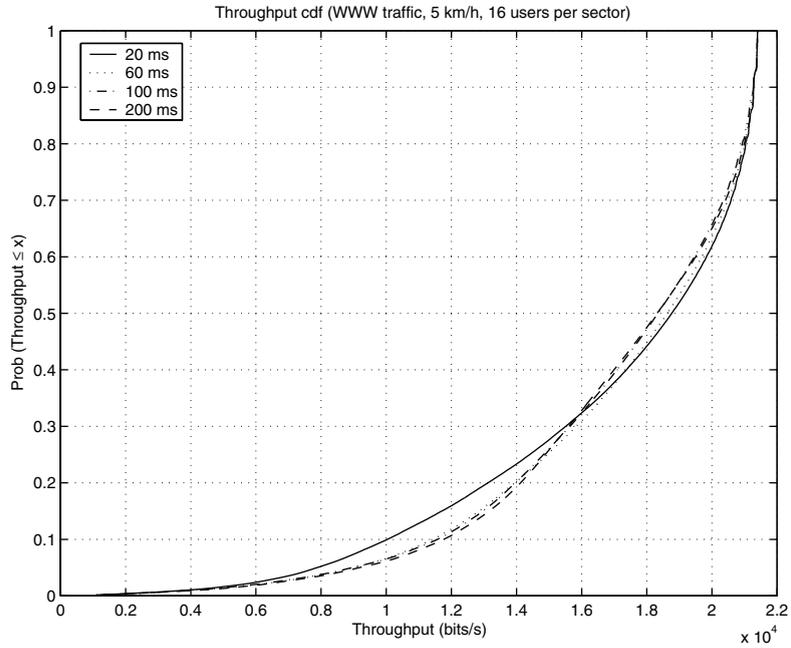Fig. 15. Throughput cdf (8 users per sector, WWW traffic, 5 km/h).

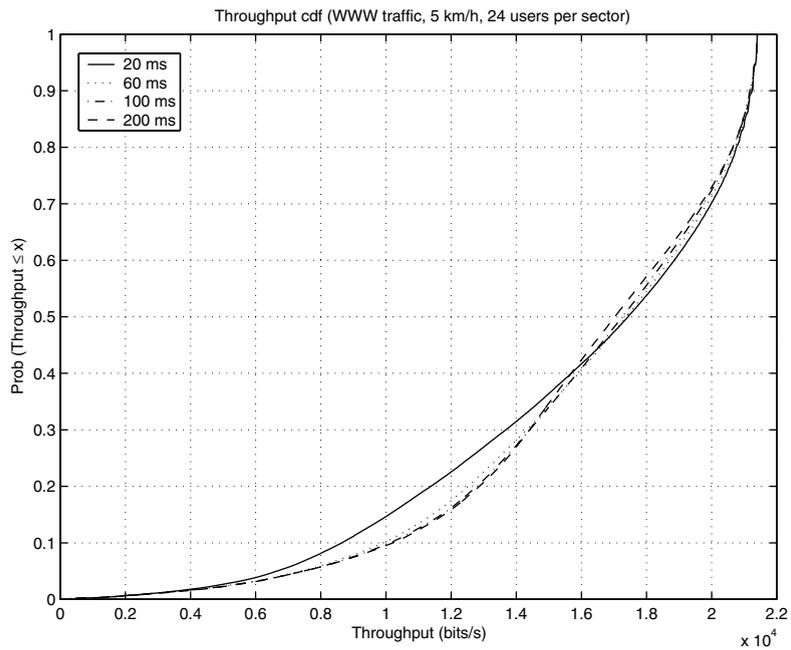Fig. 16. Throughput cdf (16 users per sector, WWW traffic, 5 km/h).

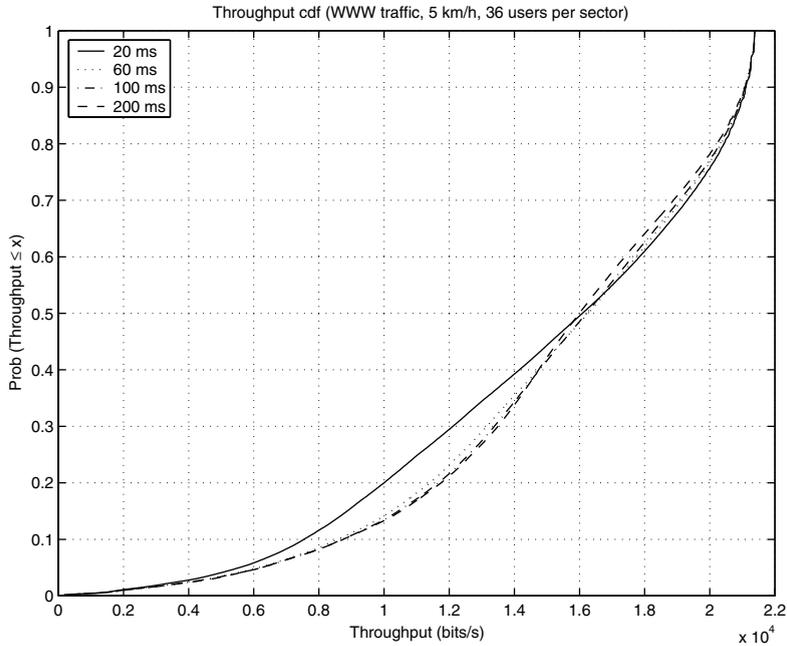Fig. 17. Throughput cdf (24 users per sector, WWW traffic, 5 km/h).

Fig. 18. Throughput cdf (36 users per sector, WWW traffic, 5 km/h).

are some differences in the trends revealed at 50 km/h and those observed at 5 km/h. First of all, direct comparison of Tables 3 and 4 also illustrates that the performance is clearly degraded at low speeds for all loads and LA updating periods considered. As it was observed at 50 km/h, a 20 ms updating period decreases, at low speeds, the throughput performance compared to a 60 ms updating period. The same effect is observed for the minimum throughput for 95% of the samples. This difference in performance is increased at 5 km/h compared to 50 km/h. Under low speeds, the 60 ms, 100 ms and 200 ms updating periods also give better throughput for 95% of the samples than a 20 ms updating period, following the trend observed at 50 km/h. However, the main difference between high and low speeds is the performance for longer LA updating periods. Table 3 shows that, at high speeds, the throughput performance decreases for the 200 ms LA updating period. As shown in Table 4, the decrease in throughput performance for longer LA updating periods is reduced at lower speeds. More importantly, Table 4 shows that, at low speeds, a LA updating period of 200 ms even provides the highest mini-

mum throughput for 95% of the samples for low and medium loads, which was not the case at high speeds. The differences observed at high and low speeds demonstrate that the selection of the optimum LA updating period, and therefore the configuration of the LA, should also take into account the user mobile speed.

Table 4
Average throughput and minimum throughput for 95% of the samples in kbits/s for different LA updating periods and loads (5 km/h)

LA up period	20 ms		60 ms	
	Avg.	Min	Avg.	Min
(a)				
Load = 8	18.22	9.71	18.43	11.24
Load = 16	17.09	7.89	17.33	8.99
Load = 24	16.04	6.66	16.34	7.37
Load = 36	15.12	5.59	15.50	6.18
(b)				
	100 ms		200 ms	
Load = 8	18.38	11.39	18.39	11.65
Load = 16	17.21	8.97	17.27	9.19
Load = 24	16.35	7.48	16.31	7.48
Load = 36	15.52	6.20	15.46	6.19

Another illustration of the different effect that the use of long LA updating periods has, for low and high speeds, is shown in Fig. 19. This figure depicts the difference in the proportion of blocks received with the optimal CS when mobiles move at a speed of 5 km/h compared to 50 km/h. It can be observed that for low loads and a 20 ms LA updating period there is a decrease of approximately 3% in the proportion of blocks received with the optimal CS for low speeds compared to high speeds. On the other hand, a 200 ms LA updating period results in an actual increase of about 1.5% in the proportion of blocks received with the optimal CS for low speeds compared to higher speeds. This observation further highlights the beneficial effect of using a longer LA updating period at low speeds and under certain operating conditions. Although this increase is not sustained at higher loads, Fig. 19 clearly shows that the decrease in the proportion of blocks received with the optimal CS for low speeds is much smaller for the longer LA updating periods than the shorter ones. This effect also influences the throughput performance.

Fig. 20 represents the throughput performance for speeds of 5 km/h and 50 km/h, a load of eight users per sector and a 200 ms LA updating period. The performance under identical conditions but for a 20 ms LA updating period is illustrated in Fig. 21. Fig. 20 shows that under a 200 ms LA updating period over 63% of the samples experience a higher throughput performance at low speeds. As illustrated in Fig. 21, this percentage is reduced to around 48% with a 20 ms LA updating period. Also, the improvement obtained at low speeds for this percentage of samples is reduced with a 20 ms LA updating period compared to a 200 ms LA updating period.

As it can be observed from comparing Fig. 20 and Fig. 12, the benefit of using longer LA updating periods at low speeds is reduced for high loads.

As previously observed for high speeds, longer LA updating periods also reduce the average number of CS changes at low speeds. At low speeds, the number of CS changes also increases with the load, for all LA updating periods. However, the effect of the different LA updating periods varies with the speed considered. Fig. 22 represents the difference in the average number of CS changes per second for mobiles moving at a speed of 5 km/h compared to 50 km/h. This figure reveals
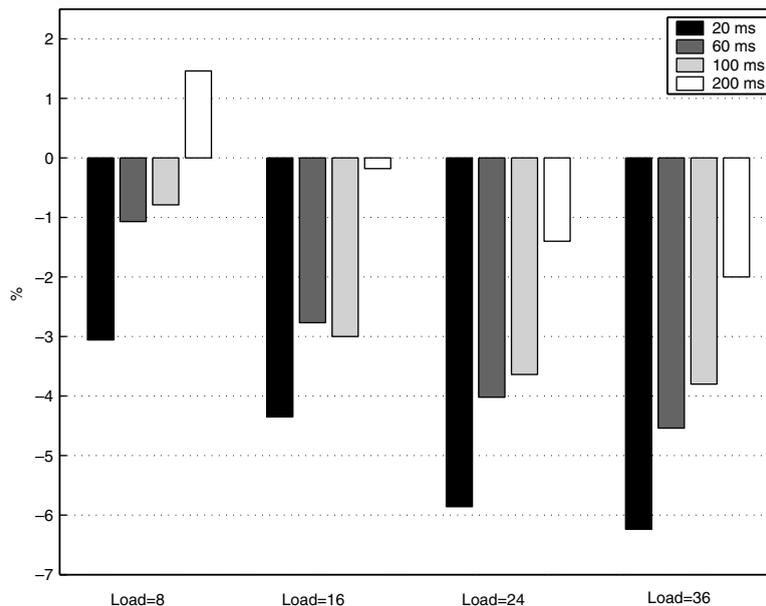

Fig. 19. Difference in the proportion of blocks received with the optimal coding scheme for 5 km/h compared to 50 km/h (WWW traffic, all loads and LA updating periods).
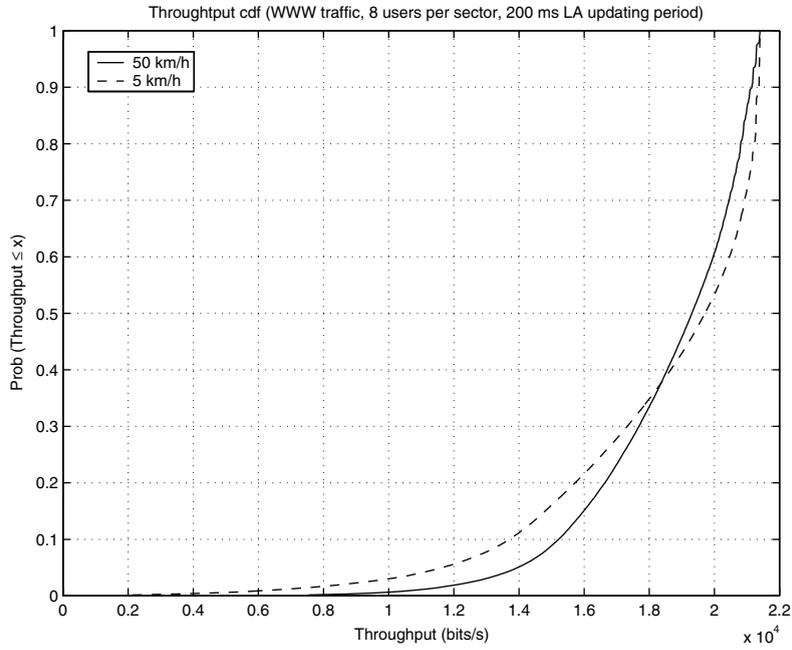
Throughtput cdf (WWW traffic, 8 users per sector, 200 ms LA updating period)

Fig. 20. Throughput cdf for a load of eight users per sector and speeds of 5 and 50 km/h (WWW traffic, 200 ms LA updating period).

Throughtput cdf (WWW traffic, 8 users per sector, 20 ms LA updating period)
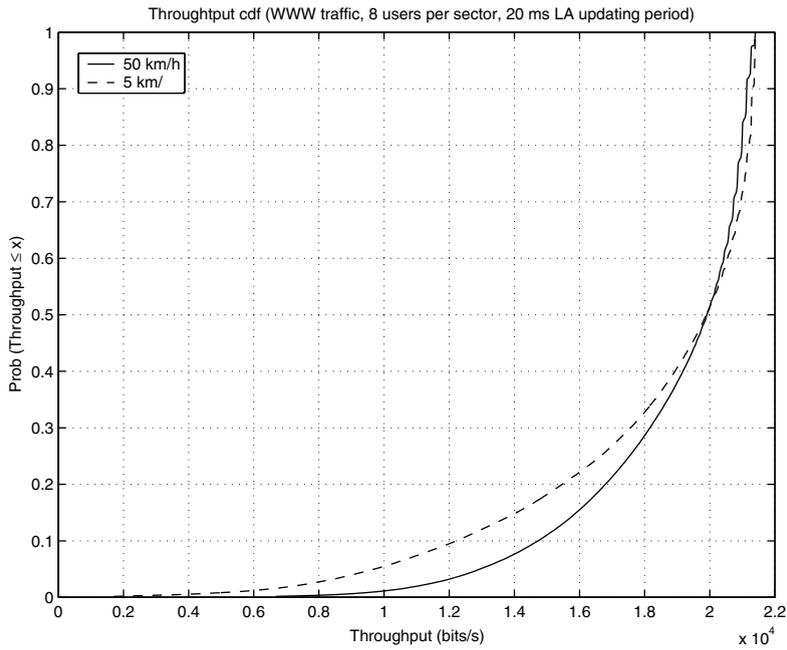

Fig. 21. Throughput cdf for a load of eight users per sector and speeds of 5 and 50 km/h (WWW traffic, 20 ms LA updating period).
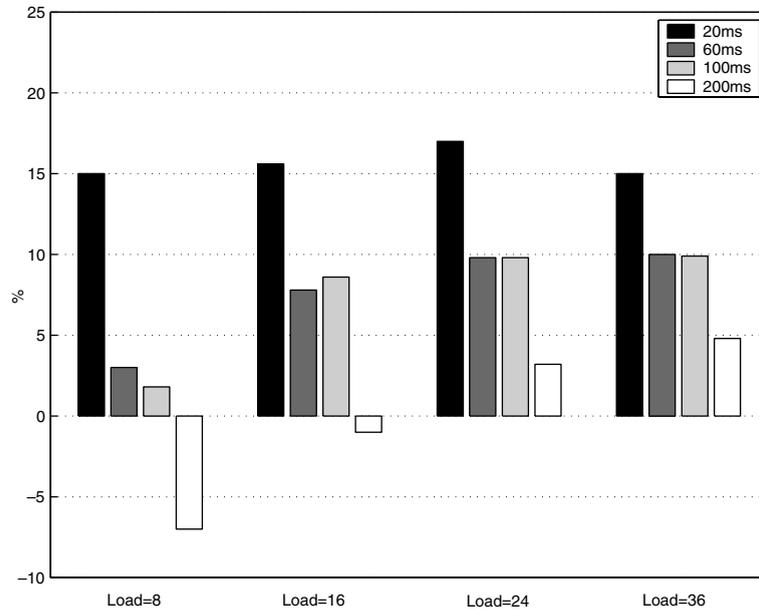
Fig. 22. Difference in the average number of coding scheme changes per second for 5 km/h compared to 50 km/h (WWW traffic, all loads and LA updating periods).

that the use of the 20 ms LA updating period with a load of eight users per sector increases by 15% the number of CS changes per second for a speed of 5 km/h compared to 50 km/h. On the other hand, the number of CS changes per second decreases by 7% for a speed of 5 km/h compared to 50 km/h if using a 200 ms LA updating period. This effect shows that, at low speeds and under certain operating conditions, the LA scheme functions better with longer LA updating periods than with shorter ones. As for the proportion of blocks received with the optimal CS, this trend is not maintained for higher loads. However, for these loads the increase in the number of CS changes at low speeds compared to higher speeds is always smaller for the longer LA updating periods.

6. Conclusions

Previous research showed that the configuration of Link Adaptation techniques should take into account operating conditions such as the system load. This paper has studied the dynamics of the LA updating periods at low user mobile speeds and under various system loads. These dynamics have been compared to those experienced at higher user speeds. The research conducted has shown that, contrary to that observed at high speeds, the use of long LA updating periods can improve the performance and operation of LA at low speeds and under certain operating conditions. Taking into account that the use of long LA updating periods also decreases the signalling load associated with the use of LA, there appears a clear benefit to using long LA updating periods at low speeds.

The results obtained from this study demonstrate that the configuration of LA should not only take into account the system load but also the user mobile speed. This conclusion further highlights the need to adapt the configuration of LA to the operating conditions.

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