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Operation and Performance of Link-Quality Based Channel Assignment Schemes in Adaptive Packet-Switched Mobile Radio Systems

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Abstract. This paper proposes and evaluates a set of physical level assisted cross-layer channel assignment schemes. These schemes allocate an incoming call the available channel that experienced the best channel quality conditions during previous transmissions. To estimate such conditions, three different link quality metrics have been considered. The performance of the proposed schemes has been compared to that of the commonly employed random allocation mechanism. The obtained results show that the proposed schemes improve the system performance of an adaptive packet-switched mobile radio system while also exhibiting the long-term channel uniform use characteristic of the random allocation mechanism. The higher performance attained with the proposed schemes is due to their short-term channel use pattern that results in an implicit cooperation among co-channel interfering cells during the channel allocation process. With the proposed schemes, interfering cells avoid assigning the same channels to simultaneous incoming calls, therefore reducing the experienced interference and increasing the system performance.

Keywords: radio resource allocation, cross-layer assisted channel assignment schemes, link adaptation, packet-switching, mobile communications

1. Introduction

The steady increase in demand for traditional voice services, the increasingly important user requirements and expectations in terms of Quality of Service (QoS), and the introduction of new bandwidth-demanding multimedia services is creating new challenges to 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 Radio Resource Management (RRM) techniques. Two increasingly important RRM techniques are channel assignment and Link Adaptation. Channel assignment schemes are in charge of allocating, managing and distributing the available channels among users and services according to some QoS or system constraints. On the other hand, LA is a radio link technique that adaptively selects a suitable transport mode according to the experienced channel quality conditions.

At present, most of the work that has been conducted regarding channel allocation techniques for packet data services in a GSM framework has focused on how to distribute and manage the available channels in an integrated GSM/GPRS scenario using the capacity-on demand concept and based on quality differentiation between services [1]. On the other hand, this work considers that a fixed number of channels are permanently assigned to the GPRS service. The channel assignment schemes will then be in charge of deciding which available channel is assigned to an incoming call.

A very commonly used allocation mechanism is random channel allocation. This scheme decides, randomly, which available channel is assigned to an incoming call. The random assignment technique offers two main advantages. The first one is its simplicity and low implementation cost. Another interesting property, from an engineering point of view, is the fact that this scheme uniformly uses all channels assigned to a given cell. As a result, it avoids surcharging particular channels and RF equipments. Another simple assignment mechanism is sequential channel allocation. This scheme assigns free channels sequentially from the start of a frame, in the case of a TDMA system. Although this procedure would increase the interference for the first channels, its design objective was to make less variable the number of interferers a user might experience. Such reduced variability was aimed at improving the operation of adaptive radio link techniques. However, the results reported in [2] clearly indicate that the initial objectives of the sequential scheme were not met and that, in fact, it underperformed the random allocation mechanism.

A common feature of the random and sequential channel assignment schemes is that they don't use any specific information for allocating channels. Some more sophisticated mechanisms that consider system and QoS information for performing their channel assignments have been reported in the literature. For example, [3] proposes different channel allocation mechanisms designed to improve blocking probability whenever half-rate and full-rate connections are considered in a GSM system. Reference [4] describes different channel allocation techniques implemented to satisfy timing requirements for transmitting video frames over a GSM network. In [5], the authors suggested, although they didn't evaluate their proposal, the possibility of assigning available channels based on their previously experienced channel quality. Based on this proposal, this paper presents and evaluates three 'intelligent' channel assignment schemes designed to improve the system performance and user perceived QoS. The considered techniques will assign an incoming call the available channel that experienced the best channel quality conditions during previous transmissions. The schemes will differentiate from each other on the metric used to evaluate the past channel quality conditions. In particular, this work considers three different metrics: mean Carrier to Interference Ratio (CIR), mean Block Error Rate (BLER) and mean Bit Error Rate (BER). The aim of this paper is not only to evaluate the potential performance improvements that can be obtained with the proposed techniques, but also to analyse and understand their operation. Such analysis will help explain the benefits offered by the proposed schemes, and as it will be shown, will also highlight new research possibilities.

2. General Packet Radio Services

The research presented in this paper has been conducted considering the General Packet Radio Services (GPRS) system, a packet-switched evolution of the GSM standard. The GPRS protocol architecture can be modeled as a hierarchy of logical layers with specific functions [6]. Since this work focuses on various aspects of the operation and performance of the GPRS radio interface, only the RLC/MAC (Radio Link Control/Medium Access Control) and physical layers have been considered.

The RLC/MAC and LLC (Logical Link Control) layers form the data link layer. The LLC layer provides a logical link between the MS and the GPRS network while the RLC/MAC layer provides functions for information transfer over the physical layer of the GPRS radio interface. These functions include procedures to establish a reliable radio link between the

Table 1. GPRS coding scheme 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

Mobile Station (MS) and Base Station (BS) and procedures enabling multiple MSs to share a common transmission medium. The physical layer has also been split into two sublayers. The Physical Link Layer (PLL) sublayer is responsible for data unit framing, data coding, and detection and correction of physical medium transmission errors while the Radio Frequency Layer (RFL) sublayer performs the modulation and demodulation of physical waveforms.

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 [6]. Each scheme has been designed to provide different resilience to propagation errors under unfavourable radio conditions. As shown in Table 1, the different CS offer a trade-off between data rate and coding protection, paving the way for the application of Link Adaptation to GPRS.

3. Proposed Channel Assignment Schemes

The three proposed channel assignment schemes assign an incoming call the available channel that experienced the best channel quality conditions during previous transmissions. The difference between each scheme is the channel quality metric considered. In this work, three metrics have been employed: Carrier to Interference Ratio (CIR), Block Error Rate (BLER) and Bit Error Rate (BER). The CIR is defined as the difference, in dB, between the received carrier signal and the received interference signal. The BLER corresponds to the number of RLC blocks received in error (detected by the Block check sequences at the receiver end) divided by the total number of transmitted blocks. Finally, the BER represents the percentage of bits received in error.

3.1. Channel Quality Metrics

The maxCIR algorithm assigns incoming calls the available channel that experienced the highest mean CIR during previous transmissions. This metric has been considered since it is commonly used to represent the channel quality variations in mobile communication systems. In fact, ETSI suggests in [7] to base the operation of LA algorithms on estimates of the CIR. Several papers in the literature have reported methods to achieve accurate CIR estimates, therefore supporting the use of CIR as a channel quality metric. For example, the algorithm described in [8] obtains CIR estimates within an error of 1 dB after only 4.6 ms (i.e., after only one frame in a GSM like system) or within an error of 0.3 dB after only 60 ms. The mean CIR used in this work is computed taking into account the interference relationships in the system, the pathloss and the shadowing, but not the effect of fast fading. Since fast fading is another important characteristic of radio propagation in mobile communication systems, a second channel assignment scheme, based on BER estimates, has been proposed. The BER values, obtained considering the effect of fast fading (see Section 4.3), are extracted at the receiver end before decoding the transmitted information. In this case, the minBER algorithm assigns the available channel that previously experienced the lower BER. The BER has been chosen as metric not only because it provides a clear indication of the channel quality conditions, but also because it has an important relation with the QoS a user might perceive. Although obtaining a BER estimate on a real system is not trivial, the work reported in [9] proposes two channel heuristics, extracted from the GSM transmission chain, that closely match the behaviour of real BER sequences.

While obtaining BER and CIR estimates could have an important implementation cost in current mobile communication systems, this is not the case of the BLER. In fact, BLER estimates are already available in GPRS-like systems since an acknowledgement report is regularly sent to the transmitter to indicate which RLC blocks were correctly received and which ones need to be retransmitted. As a result, this paper finally proposes the minBLER algorithm. This scheme assigns to an incoming call the available channel that previously experienced the lowest BLER. Another characteristic that differentiates the BLER metric from the two other metrics considered in this work, is the fact that a BLER estimate is obtained taking into account the decoding capabilities of the coding scheme used to transmit an RLC block. Therefore, the BLER provides a good indication of the final user perceived QoS. This characteristic might result particularly important when considering an adaptive mobile system that changes the modulation and/or coding scheme according to the channel quality variations.

3.2. Operation of the Proposed Schemes

The operation of the proposed algorithms is as follows. Each channel is being provided with an array used to store the channel quality measures obtained during the previous transmissions. As it will be shown in this paper, the array size is a key parameter for the performance and operation of the proposed schemes. While BER and CIR samples are stored for each transmission burst (i.e., each 4.6 ms considering single slot transmissions), BLER values are only stored for each transmitted RLC block (i.e., each 20 ms). Once the array has been filled, the oldest samples are discarded in order to store the new ones. When an incoming call requests a new channel, the proposed algorithms obtain a channel quality estimate for each one of the available channels. Each estimate is obtained by filtering all the measurements stored on each channel's array. In this paper, a filter with a rectangular shape has been employed. If the minBER or minBLER schemes are considered, the incoming call will be assigned the available channel with the lowest average channel quality estimate. On the other hand, for the maxCIR proposal, the assigned channel will be the one with the highest average channel quality estimate. The operation of the proposed channel assignment schemes is summarised in Figure 1.

4. System Level Evaluation Platform

The performance evaluation of a cellular system is usually conducted at two different levels: system level and link level. The system level models a mobile radio network taking into account aspects such as mobility and interfering relationships among mobiles. On the other hand, link level simulations model the radio link at bit level. The reason for separating the analysis into

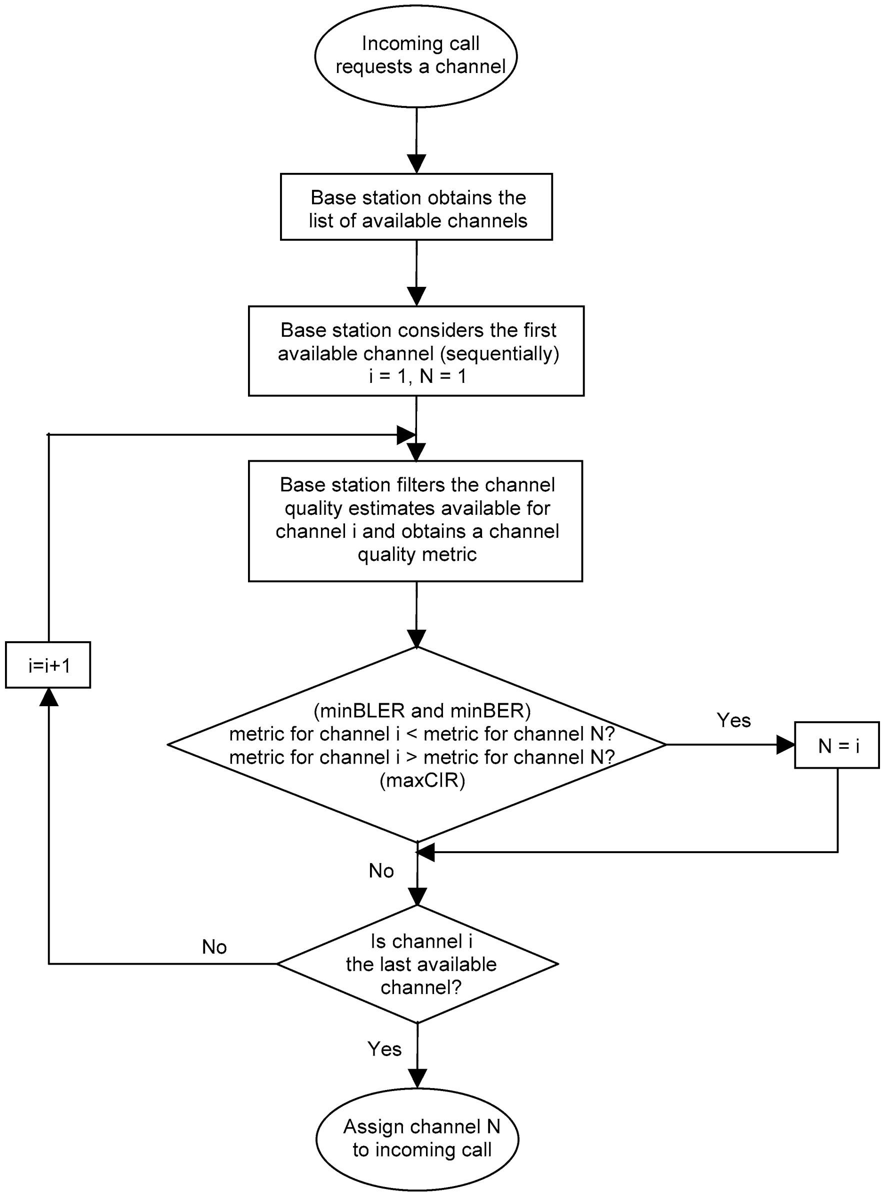

Figure 1. Operation of the link-quality based channel assignment schemes.

two levels is the different time resolution needed to study link or system related aspects, and the high computational requirements generally associated with the link level analysis. Interfaces between the two levels are then necessary to analyse the overall performance. For that purpose, link-to-system level interfaces, that use the link level results as a source of information for the system level, are generally employed.

4.1. System Environment

The system level analysis has been conducted using an event-driven simulator working at the burst level. The time-scale resolution considered ensures a high modelling accuracy and allows accounting for sudden channel quality variations. The simulator models a cellular network of equally sized 3-sector macro cells, with a cluster size equal to four. Each cell has a radius of 1 km and each sector has been assigned two carriers (i.e. 16 channels or time slots). The boundary effects have been removed using a wrap-around technique. Since the simulator models the interference produced by the first and second tiers of co-channel interferers, the simulator models 25 co-channel cells.

The channel quality dynamics are measured by means of the CIR. Pathloss is predicted using the Okumura-Hata model. Although this model was based on measurements done for distances greater than 1 km, the model can be extended for distances below 1 km [10]. The shadowing is modelled by means of a log normal distribution with a standard deviation of 6 dB. The spatial correlation characteristic of the shadowing has been implemented using the model described in [11]. Following the observations reported in [12], a decorrelation distance of 20 meters has been considered for the macrocellular suburban environment under study. Fast fading has also been included in the system level simulations as explained in Section 4.3. Power Control (PC) or Slow Frequency Hopping (SFH) have not been implemented in the simulator. In fact, PC and SFH directly affect the operation of LA since they modify the channel quality conditions. As a result, 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 implemented.

The simulator concentrates on the downlink performance. A load of eight users per sector, with each user operating for the complete duration of the simulation, has been considered for this study. Users are assigned channels in a first-come-first-served basis and the channel is kept until all its data has been correctly transmitted. In this study, only single slot transmissions have been considered. Users can move at a speed of 50 km/h within each sector, but no handover between sectors has been considered. As a result, mobile stations are connected to the closest base station and not to the best serving base station.

4.2. Traffic Modelling

Two of the most popular data traffic applications, WWW browsing and email, have been implemented by means of analytical models. 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. For both traffic sources, implemented as ON/OFF 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 using the model described in [13]. This model considers that a separate TCP connection is needed to transfer each file, or object, in a web page. Each connection is closed after the transmission is finished and a new connection must be established for the transfer of a new file. E-mail traffic has been generated following the model presented in [14], where the email size distribution is bi-modal as emails are also used to transfer files.

Since this work considers data applications that require a highly reliable transmission, a selective Automatic Repeat reQuest (ARQ) protocol has been employed to request the retransmission of erroneous blocks. The protocol has been implemented following the GPRS specifications [6]. The ARQ window size is equal to 64 RLC blocks and an ARQ report is sent after transmitting 16 RLC blocks [15]. A perfect feedback of the ARQ report has been assumed.

4.3. Link-to-System Level Interfaces

In order to reduce the complexity of system level simulations, 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 BLER. Different LUTs need to be produced for different operating conditions (e.g., mobile speeds and propagation environments). Depending on the particular study that is being carried out at the system level, different levels of accuracy can also be targeted in the production of the LUTs. Simplified look-up tables are generally considered in system level investigations. However, the work reported in [16] 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. As a result, an advanced set of LUTs has been implemented to conduct this research. The LUTs have been produced using the high-speed link level simulator detailed in [17].

To accurately model RLC block errors, the implemented link-to-system level interface works at the burst level. As a result, block errors can be modelled not only as a function of the mean block quality but also of the quality distribution among the four bursts used to transmit an RLC block. Such modelling approach is necessary due to the combined effects of convolutional coding and interleaving.

The interface, composed of two sets of LUTs, 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 BER extracted before the channel decoding process. As shown in Figure 2, LUT-1 represents a cumulative distribution function (cdf) of

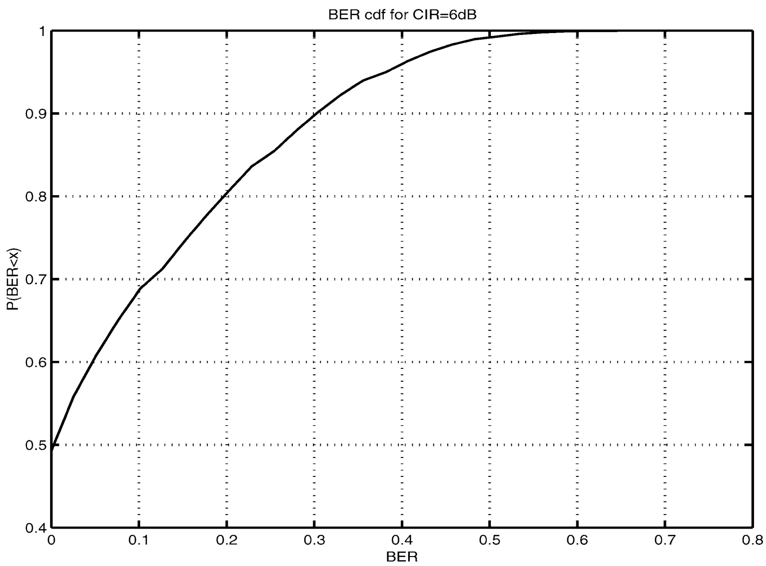

Figure 2. LUT-1 – BER cdf for a CIR equal to 6 dB.

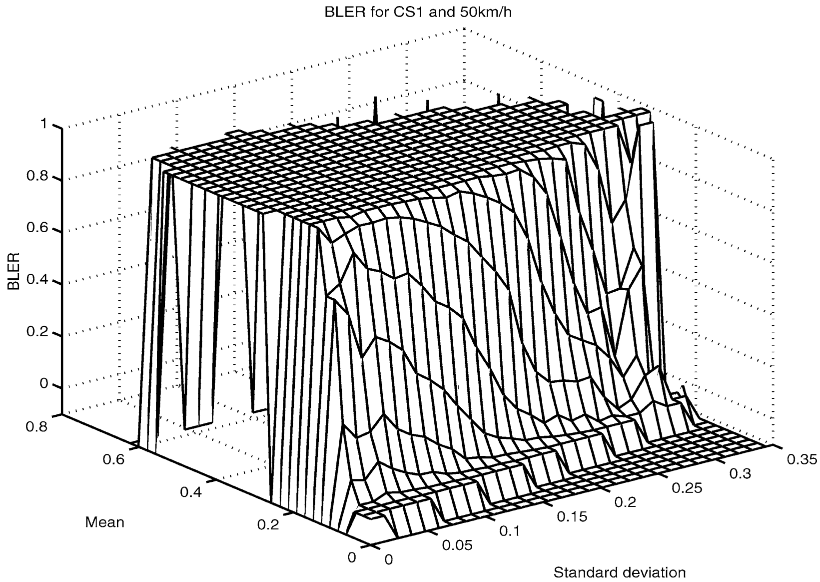

Figure 3. LUT-2 – BLER vs mean and standard deviation of BER (CS1).

the BER for a given CIR. As a consequence there will be a burst quality cdf for each local mean 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 an RLC block and LUT-2 maps the mean BER and the standard deviation of the BER over the four bursts to a corresponding BLER value.

Figure 3 illustrates an example of LUT-2 for CS1[1]. The different LUTs used in this study have been developed for a typical urban environment that does not consider the use of frequency hopping, and a mobile speed of 50 km/h.

5. Link Adaptation Algorithm

The main focus of this paper is the study of new link-quality based channel assignment schemes. However, since the use of adaptive radio link techniques is becoming increasingly important for the evolution of both 2G [18] and 3G systems [19], the study has been conducted for an adaptive packet-switched mobile radio system employing LA. The channel quality dynamics can be influenced by the mechanism used to assign free channels. In fact, it has even been proposed to exploit the flexibility in which channels can be allocated in packet-based systems to shape the interference within a system [20]. The idea behind such proposal is to benefit the performance of LA and other adaptive techniques by producing more stable link quality conditions. Since the operation of techniques like LA depends on the channel quality dynamics, this work also estimates how the proposed channel assignment schemes affect the performance and operation of LA.

[1] 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 mean and standard deviation of burst quality never occurred in the link level simulations.

The basis of LA is to assess the channel conditions and then use a transport mode (i.e. modulation and/or coding scheme) that is optimised for these conditions. Since GPRS considers a single modulation scheme, the adaptation will be done at the coding scheme (CS) level. The current GPRS standard does not contemplate CS changes for retransmissions when considering the application of LA, as it is the case of EDGE (Enhanced Data rates for Global Evolution) [18]. However, in this research such changes have been considered so that results are not conditioned by GPRS limitations.

Different approaches can be taken to decide which CS is considered as optimum based on, for example, the targeted QoS for a given service. In [21], the authors propose a LA algorithm that seeks to minimise transmission delays while the work reported in [22] proposed a scheme designed to achieve a target error rate. Since this work is based on non-real time data services (WWW and e-mail), a CS is considered to be optimum if it maximises the throughput. The criterion here considered for selecting a particular coding scheme is also proposed in [18] for the study of EDGE. The throughput is defined as follows:

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

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. Taking into account the particular link-to-system level interface considered in this work, an example of the throughput performance used to define the LA switching thresholds is illustrated in Figure 4. As it can be observed from this figure, the LA switching thresholds are defined as a collection of points, each representing a combination of mean and standard deviation of burst quality values. It is also important to note the limited operating area of CS4 compared to the other CS. Since CS4 does not have any error protection, the LA algorithm will only consider it as the optimum CS when experiencing no errors

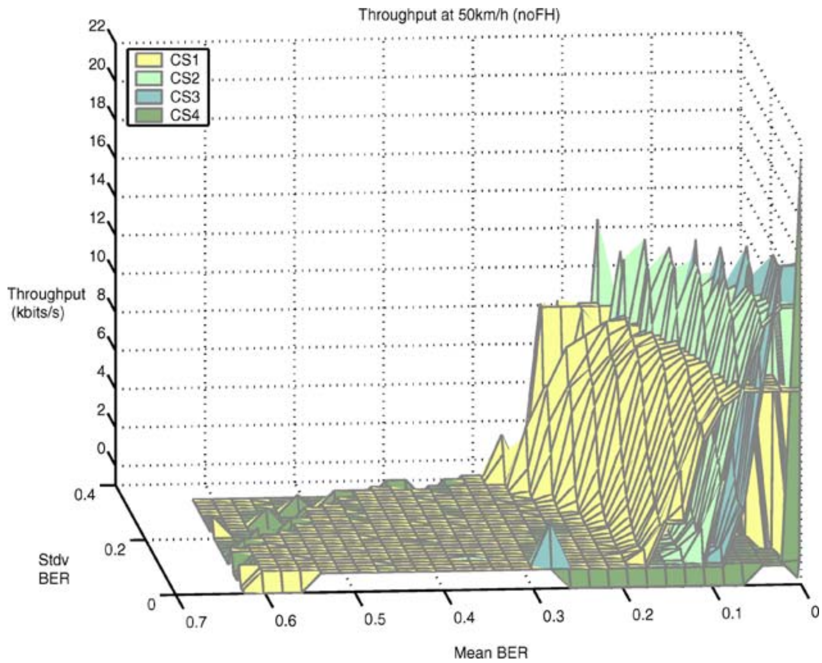

Figure 4. Throughput performance and LA switching thresholds.

during radio transmissions. For this study, no hysteresis thresholds around the LA switching boundaries have been considered.

The LA algorithm uses the quality measurements over the previous LA updating 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 updating period are filtered to get the quality measurements necessary for the LA algorithm. This work has considered a simple filter with a rectangular shape that weights all channel quality measurements equally. The LA updating period defines how regularly a decision is made on the most suitable CS. Following the observations reported in [23], a 100 ms LA updating period has been considered for this study. In this work, a fixed initial coding scheme, CS4, has been selected at the beginning of each new data transmission.

6. System Evaluation

This section presents an exhaustive evaluation of the system performance obtained with the three proposed channel allocation mechanisms. The random channel allocation mechanism has been selected as the reference scheme against which to compare the performance of the three proposed algorithms. Such choice has been made because of its simplicity, good performance and widespread adoption.

6.1. Evaluation Parameters

Since this work is based non-real time data services, the system throughput has been considered as the main performance metric. 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. In this case, the throughput is measured over intervals of four seconds whenever the user is active. As a result, the throughput does not take into account the time a user has been waiting to get access to a channel. The throughput is collected for all users in the central cell of the simulated network and the cdf (cumulative distribution function) of the throughput is used to provide an indication of the system performance. Of particular interest is not only the mean performance (averaged over all users in the central cell), but also the highest minimum performance guaranteed for 95% and 99% of the samples. These two parameters, extracted from the system cdf, represent the performance for the users experiencing a worse service. As a result, they are used to analyse the fairness of the proposed channel assignment schemes. Other parameters of interest are the BER, BLER and normalized delay. The BER and BLER measures are also calculated over radio transmission intervals of four seconds. The normalized delay is defined as the time needed to transmit a block of data divided by the size of such block.

The configuration of LA could be regarded as optimum if it maximises the performance while minimising the signalling load associated with its use. Such signalling load has been estimated by means of the average number of CS changes per second requested by the LA algorithm. Other useful parameters to understand the operation of LA are the proportion of RLC blocks received with an optimal CS, the proportion of wrong-side and right-side failures, and the mode error for each CS. A right-side failure corresponds to the case where a user is using a non-optimal CS but one robust enough to guarantee the correct reception of the transmitted data. For the wrong-side failure, the current CS is not robust enough. The mode

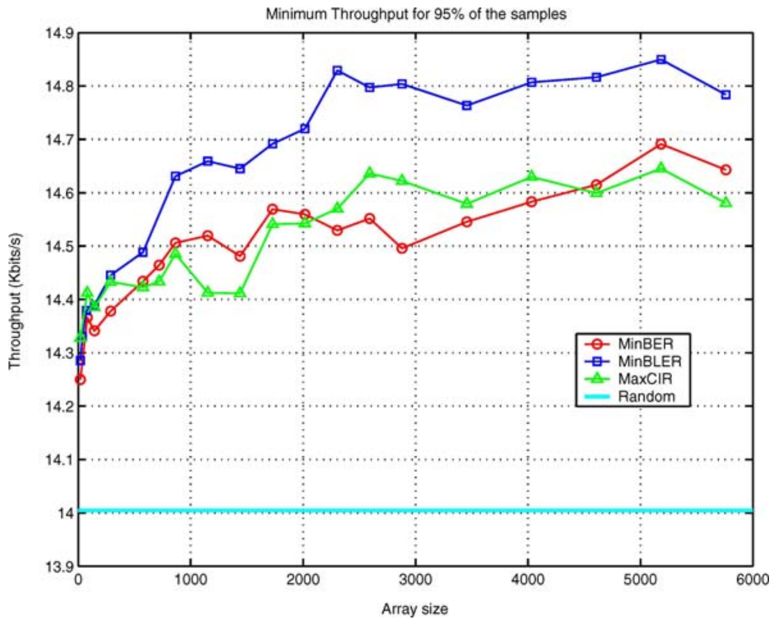

Figure 5. Minimum throughput for 95% of the samples.

error represents the percentage of time that a given CS was being used and it was not the optimal one.

Finally, it is important to note that in order to ensure results with good statistical accuracy, each simulation scenario simulates the transmission of more than 30 million RLC blocks in the central cell.

6.2. System Performance

Figure 5 illustrates the minimum throughput experienced by 95% of the samples considering the three proposed channel assignment algorithms and the random scheme. The throughput performance is plotted as a function of the array size used by the proposed schemes to store channel quality measures obtained during previous transmissions. Several important conclusions can be extracted from this figure. First of all, the figure demonstrates that the proposed schemes outperform the random assignment mechanism. The scheme achieving the highest throughput performance is minBLER. As it has been previously mentioned, BLER estimates reflect the error correcting capabilities of the CS used during radio transmissions. This is not the case for the BER and CIR measures since they are obtained before performing channel decoding. As a result, while the BLER provides a clear indication of the user perceived QoS, the effect of the BER and CIR on such QoS will still depend on the employed CS.[2] This difference results in improved channel assignment decisions using the minBLER scheme compared to using the minBER and maxCIR proposals.

Figure 5 also shows the strong influence of the array size on the performance of the three proposed schemes. In particular, the obtained results indicate that the performance increases with the array size. This is due to the fact that using larger number of channel quality measures,

[2] This is particularly important when considering LA since it dynamically changes the employed CS.

Table 2. Effect of the array size on the operation of the proposed schemes

	minBLER			minBER			maxCIR		
Array size	20	864	2880	20	864	4608	20	864	4032
Optimal CS (%)	76.84	77.93	78.54	76.71	77.63	77.92	76.97	77.5	78.02
Right-side failures (%)	18.29	17.44	16.96	18.39	17.67	17.44	18.18	17.77	17.36
Wrong-side failures (%)	4.87	4.63	4.5	4.9	4.7	4.64	4.85	4.73	4.62
CS4 usage (%)	74.45	76.04	76.91	74.27	75.57	76.03	74.64	75.41	76.15
CS4 mode error (%)	4.59	4.42	4.31	4.62	4.46	4.42	4.57	4.48	4.4

it is possible to obtain a more reliable and representative average estimate of the previously experienced channel quality conditions. As shown in Table 2, average estimates obtained using a larger number of measures help to better predict the channel quality and therefore to improve the channel assignment process; i.e. they increase the probability of assigning the channel that will experience the best quality conditions in future transmissions. Table 2 indicates that with larger array sizes, not only does the percentage of blocks received with the optimal CS increase but also the usage of CS4.[3] It is important to remind that CS4 is the coding scheme that transmits the higher payload in an RLC block and that its use is considered when operating under good radio conditions. As a result, a higher use of CS4 is actually an indication that the channel quality conditions have improved.

Figure 5 indicates that the minBLER algorithm improves its throughput performance with the array size but only up to an array size of 2304 measurements. Increasing further the array size does not significantly improve the performance. On the other hand, increasing the array size results in a higher implementation cost of the proposed scheme since larger memory sizes are needed to store the additional channel quality measures.[4] As a result, increasing the array size beyond 2304 measurements will result in an unjustified extra implementation cost. As illustrated in Figure 5, very similar observations can be made for the maxCIR and minBER techniques. In their case, the higher throughput performance was obtained for array sizes of 2592 and 5184 respectively.

Figures 6 and 7 depict, respectively, the average throughput and minimum throughput experienced by 99% of the samples. It can be observed that the same conclusions regarding the effect of the array size on the algorithm's performance can be obtained for these two other performance parameters.

Figures 8 and 9 show that the minBLER scheme results in better experienced channel quality conditions (i.e. lower BER and BLER). This improved link quality is at the origin of the higher throughput performance attained with the minBLER proposal. As depicted in Figure 10, a higher throughput performance results in lower transmission delays and therefore higher user satisfaction.

Table 3 reports the system performance of the three proposed schemes considering their best array size.[5] The table also indicates the improvement (in %) achieved with the proposed

[3] The mode error for CS4 also decreases.

[4] Apart from some extra computations required to obtain the average channel quality estimates, the implementation cost of the proposed schemes is mainly the memory needed to store the channel quality measurements. Since the required computations are done at the base station, their actual cost can be considered as minimum.

[5] minBLER scheme: array size of 2304 measurements; maxCIR scheme: array size of 2592; minBER scheme: array size of 5184.

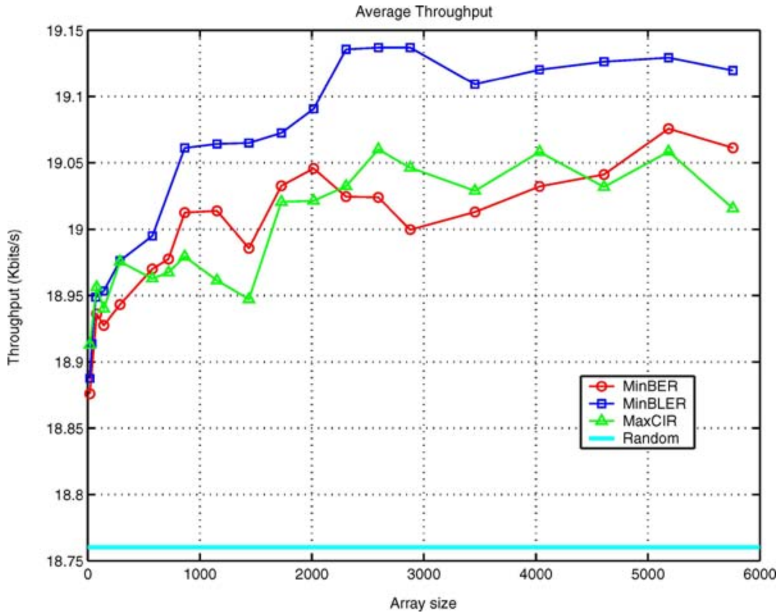

Figure 6. Average throughput.

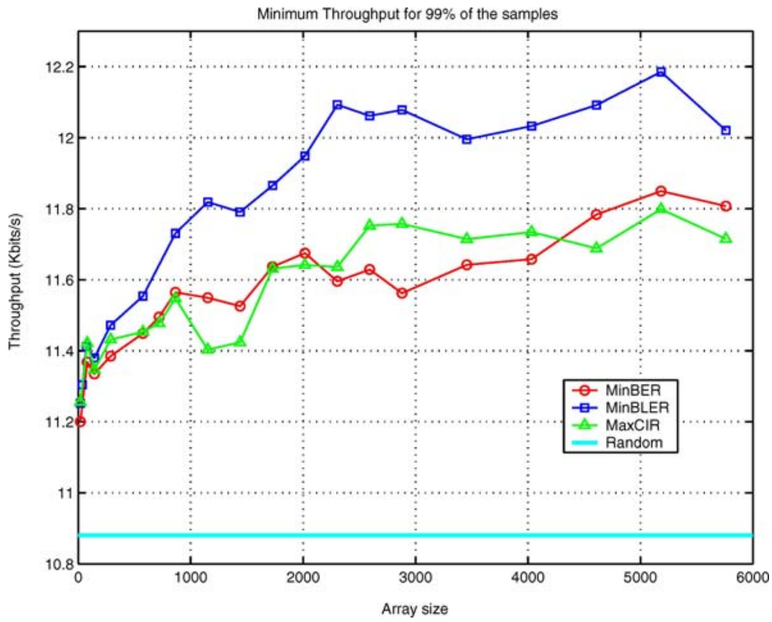

Figure 7. Minimum throughput for 99% of the samples.

techniques compared to the random allocation mechanism. Table 3 shows that while the gains obtained with the proposed schemes could be regarded as not very important in terms of the mean performance (throughput and normalized delay), the minimum guaranteed QoS[6] is

[6] Minimum throughput for 95 and 99% of the samples, and highest normalized delay for 95% and 99% of the samples.

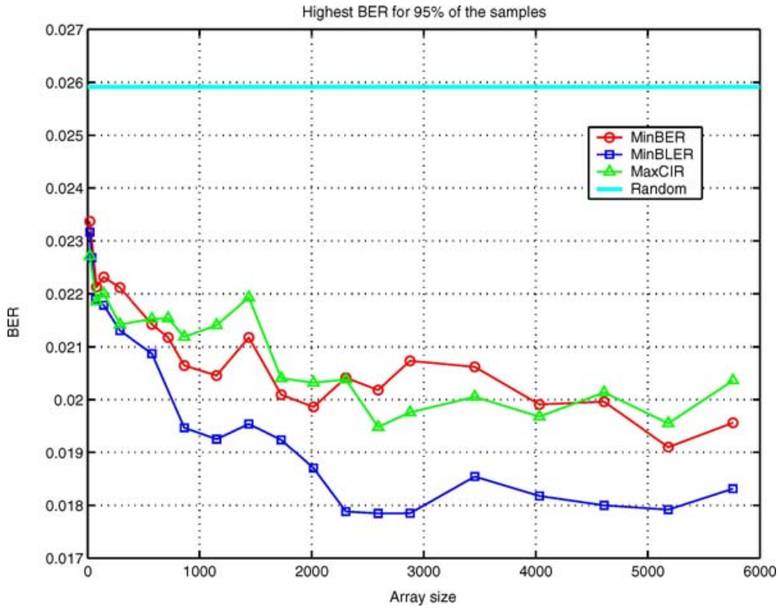

Figure 8. Highest BER for 95% of the samples.

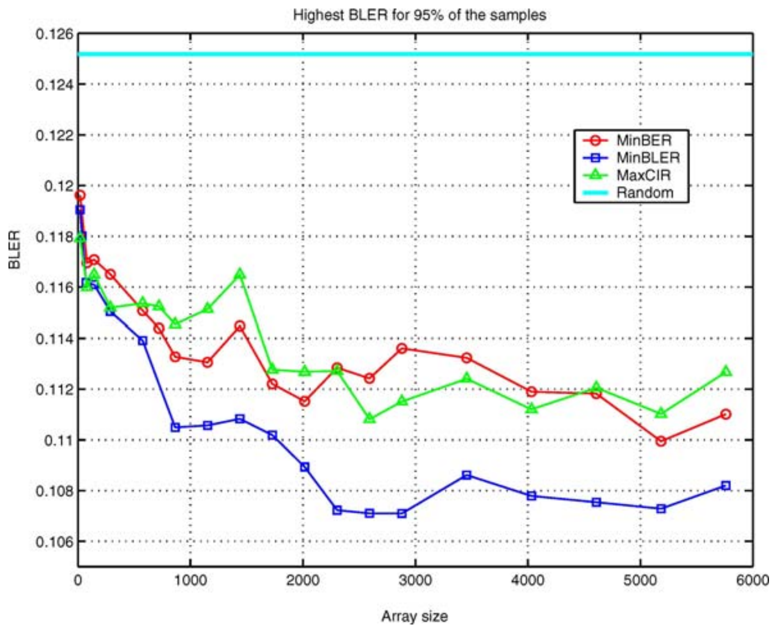

Figure 9. Highest BLER for 95% of the samples.

greatly improved. It can therefore be concluded that the proposed schemes greatly improve the QoS for the users experiencing a worse performance, which results in a fairer system operation compared to the random allocation mechanism. As depicted in Table 3, this enhanced operation has been obtained without degrading the system performance.

The results shown in Table 3 indicate that the improvements obtained with the proposed schemes are due to their better operating channel quality conditions. It can also be observed

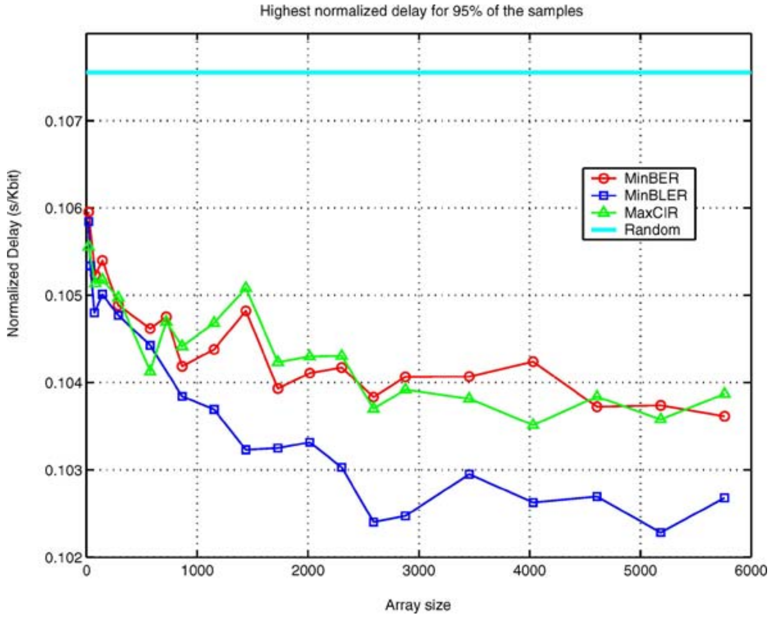

Figure 10. Highest normalized delay for 95% of the samples

Table 3. System performance

	Random	MinBLER		MinBER		MaxCIR	
	Perf.	Perf.	Impr.	Perf.	Impr.	Perf.	Impr.
Mean throughput (kbits/s)	18.76	19.14	2.03%	19.08	1.7%	19.06	1.6%
Minimum throughput for 95% of samples (kbits/s)	14	14.83	5.9%	14.69	4.9%	14.64	4.6%
Minimum throughput for 99% of samples (kbits/s)	10.88	12.09	11.14%	11.85	8.9%	11.75	8%
Mean normalized delay (ms/kbit)	69.4	67.7	2.45%	67.9	2.16%	67.9	2.16%
Highest normalized delay for 95% of samples (ms/kbit)	107.6	103	4.28%	103.7	3.63%	103.7	3.63%
Highest normalized delay for 99% of samples (ms/kbit)	141.1	129.4	8.3%	131.5	6.8%	131.6	6.73%
Average BLER (%)	4.97	4.32	13.08%	4.42	11.07%	4.45	10.46%
Highest BLER for 95% of samples (%)	12.52	10.72	14.38%	10.99	12.22%	11.08	11.5%
Highest BLER for 99% of samples (%)	21.58	17.38	19.46%	18.13	15.99%	18.41	14.69%
Average BER (%)	0.55	0.39	29.09%	0.41	25.45%	0.42	23.64%
Highest BER for 95% of samples (%)	2.59	1.79	30.89%	1.91	26.25%	1.95	24.71%
Highest BER for 99% of samples (%)	6.48	4.73	27.01%	5.05	22.07%	5.18	20.06%

that BER improvements are generally much higher than the ones obtained for the BLER and for the QoS (throughput and normalized delay). This is due to the fact that BER values have been obtained without considering the error correcting capabilities of the employed CS. As a result, whether a lower BER would result in a lower BLER will still depend on the CS used and how the erroneous bits are distributed within the four bursts used to transmit an RLC block.

Table 4. Operation of Link Adaptation

	Random	MinBLER		MinBER		MaxCIR	
	Perf.	Perf.	Impr.	Perf.	Impr.	Perf.	Impr.
Average nb of CS changes per second	2.227	2.062	7.41%	2.089	6.2%	2.093	6.01%
Optimal CS (%)	75.86	78.56	3.6%	78.14	3%	78	2.82%
Right-side failures (%)	19.05	16.94	11.08%	17.27	9.34%	17.38	8.77%
Wrong-side failures (%)	5.09	4.5	11.6%	4.59	9.82%	4.62	9.23%

6.3. Interaction with the Operation of Link Adaptation

Table 4 shows that the proposed schemes have a positive effect on the operation of Link Adaptation. In particular, the schemes increase the percentage of blocks received with the optimal coding scheme and reduce the percentage of wrong-side and right side failures. The minBLER proposal is the one resulting in the best LA operation. These results clearly indicate that when considering the proposed schemes, the LA algorithm improves its CS selection process. Such improved operation results in a lower average number of CS changes per second requested by the LA algorithm, and therefore, in an important reduction of the signalling load associated with its use.

7. Operation of the Proposed Channel Assignment Schemes

The results reported in the previous section have demonstrated that the proposed schemes outperform the random channel allocation mechanism. The higher performance achieved with the proposed schemes does not come at the expense of a very important implementation cost. In fact, the cost has been shown to be quite low for the most efficient algorithm, minBLER. Apart from its simplicity, a key advantage of the random allocation mechanism is that it guarantees a long-term uniform use of all channels, avoiding then the surcharge of particular channels and RF equipment. The next step in this work has been to check whether the proposed algorithms maintain this interesting property from an engineering point of view.

Figure 11 plots the average occupancy time of each channel considering the proposed schemes, using their best array sizes, and the random allocation technique.[7] This figure shows that the proposed mechanisms exhibit the same long-term uniform use of all channels, and therefore RF equipment, as the random allocation scheme.

This section demonstrates that the reason why the proposed schemes outperform the random allocation mechanism is not their long-term channel use pattern but the short-term one. In particular, the short-term channel use pattern exhibited when considering the use of the proposed schemes will result in a cooperation among co-channel interfering cells that reduces the interference level and increases the system performance. It will also be shown that to improve the system performance and guarantee a long-term uniform use of all channels, the proposed

[7] This figure corresponds to the average occupancy time across all cells modelled in our system. However, since all cells experience the same operating conditions (i.e. number of interfering cells, user load, traffic characteristics, etc), on the long term, the results obtained in a single cell will tend towards the average across all different cells. This assertion has been verified for the minBLER algorithm.

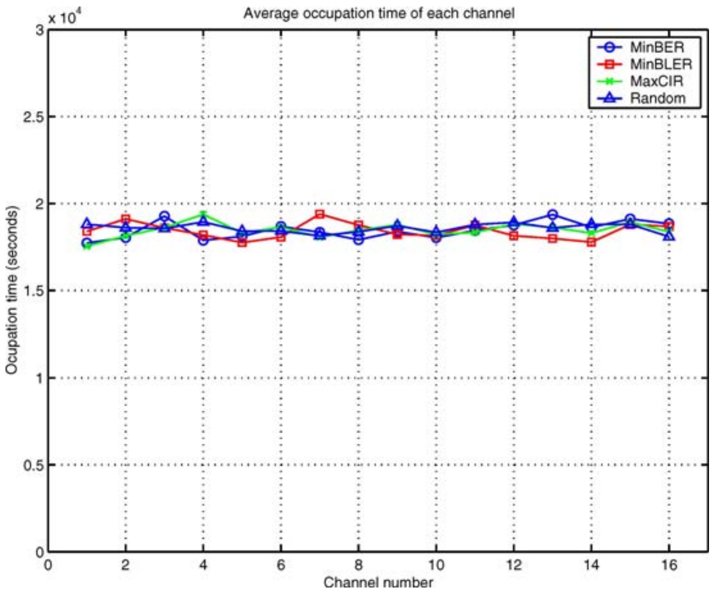

Figure 11. Long-term average channel occupancy.

schemes need to periodically reset the arrays used to store the channel quality measurements obtained during previous transmissions.

To better explain these assertions, a closer look at our simulation approach and the modeled cellular system is required.

The simulations have been conducted using the independent replication/deletion method [24]. This method consists in running *n* statistically independent simulation replications, each one using a different seed for the random number generator. Since the simulations are usually driven by random samples obtained from random number generators, using a different seed for each replication is equivalent to starting the emulation process under different initial conditions. The resulting output variables are then averaged over all the runs to get the final system performance. The number of runs and the duration of each run have been set to values allowing a good statistical estimate of the system characteristics under evaluation. The relative error of the observed mean values was kept below 0.01 in most cases.

In terms of the modeled cellular system, Figure 12 illustrates the implemented cellular layout. Cell 44 is considered the central cell of our system. All the results shown in previous sections have been extracted from the central cell. Since a sectorized cellular network has been considered, the cell 44 receives interference from cells 42 and 24 (first tiers), and cells 60, 22, 6, 40 and 4 (second tiers). It is also important to note that the cell 42 will also receive, among others, interference from cells 40, 22 (first tiers) and 4 (second tiers). Users in cell 24 will be interfered by users in cells 22, 4 (first tiers) and 40 (second tiers).

Figure 13 shows the channel occupancy, at the end of a single simulation run, in the central cell (cell 44) and in its two first tiers co-channel interferers (42 and 24). This figure corresponds to the minBLER algorithm and an array size equal to 2304 channel quality measurements. It is important to keep in mind that Figure 11 was obtained averaging the results of a large number of simulation runs while Figure 13 corresponds to the channel occupancy at the end of a single simulation run. Consequently, Figure 11 provides an indication of the long-term channel occupancy pattern and Figure 13 of the short one. Comparing Figures 11 and 13, it

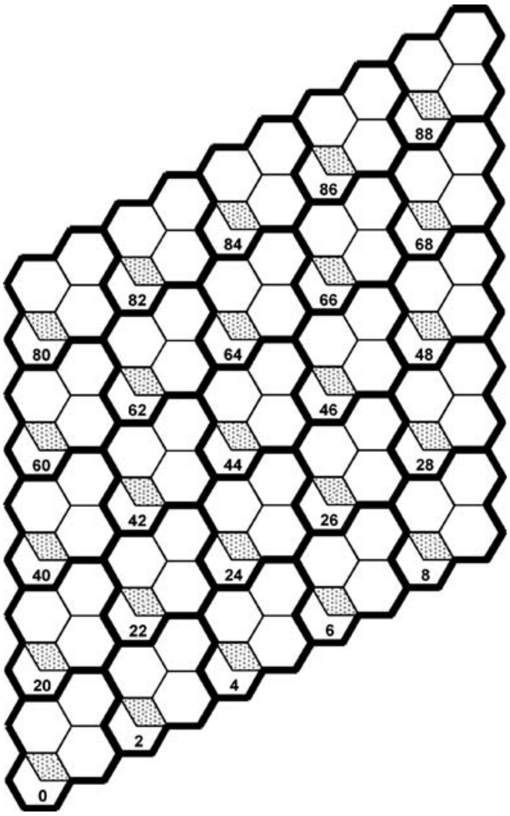

Figure 12. Cellular system layout

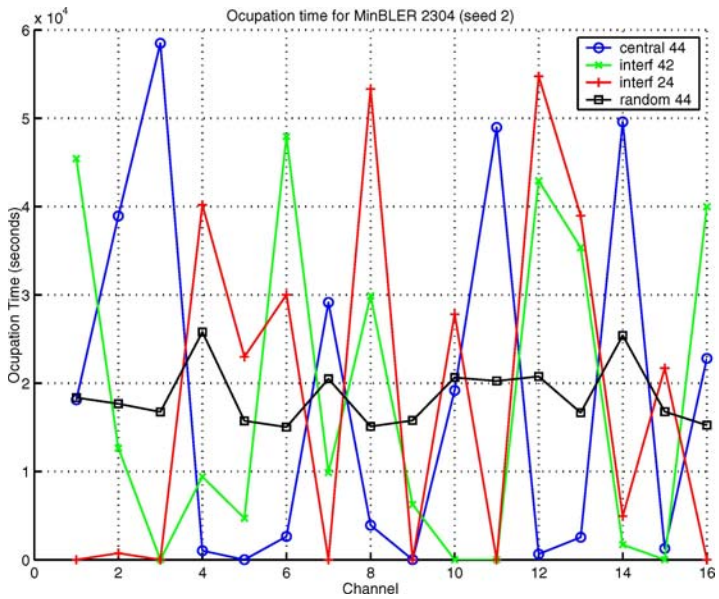

Figure 13. Channel occupancy in cell 44 and its first tiers co-channel interfering cells (minBLER scheme, array size = 2304, single simulation run with seed = 2).

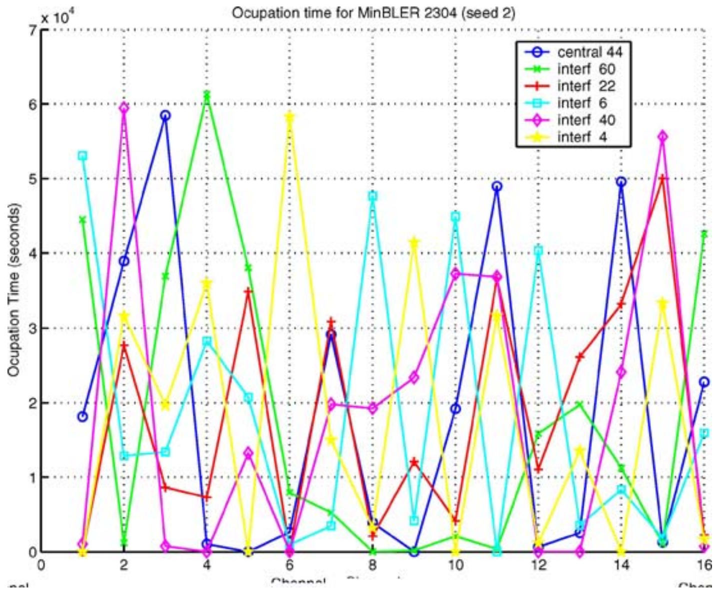

Figure 14. Channel occupancy in cell 44 and its second tiers co-channel interfering cells (minBLER scheme, array size = 2304, single simulation run with seed = 2).

can be observed that the long-term and short-term channel use patterns are quite different for the minBLER algorithm. On the other hand, the random channel allocation scheme exhibits a very similar channel use pattern in the long and short terms. The observed differences in the short-term channel use pattern, between the proposed schemes[8] and the random allocation mechanism, are at the origin of their different system performance. In fact, Figure 13 shows that, for the minBLER scheme, interfering cells avoid using the same channels at the same time. For example, it can be observed that while the use of channel 11 is avoided in the first tiers co-channel interferers, it is greatly used in the central cell. This is due to the fact that when the BS detects that a channel is experiencing good channel quality conditions, it would continuously assign such channel to incoming calls. Such good channel conditions are obtained because the co-channel interferers are avoiding using the same channel. The reason why cells 42 and 24 avoid using channel 11 is because their first tiers co-channel interferers (40, 22 and 4) are continuously transmitting in channel 11; see Figure 14. Very similar situations as for channel 11 occur for channels 2, 3, 7 and 14. Following a similar reasoning, the use of channel 12 in the central cell is avoided since this channel is importantly used in its interfering cells. The same situation occurs for channels 4, 5, 6, 8, 9, 13 and 15. As a result, it has been observed that the proposed schemes provoke an implicit cooperation among co-channel interfering cells during the channel allocation process. Such cooperation guarantees a lower instantaneous interference level, compared to the random allocation mechanism, and therefore a higher performance.

Figure 14 shows that the implicit cooperation among a cell and its second tiers interferers is not always guaranteed. This situation arises when a second tiers interferer of the central cell is also a first tiers interferer for a first tiers interferer of the central cell. This can be again

[8] The minBER and maxCIR schemes exhibit similar short-term channel use patterns as the minBLER proposal.

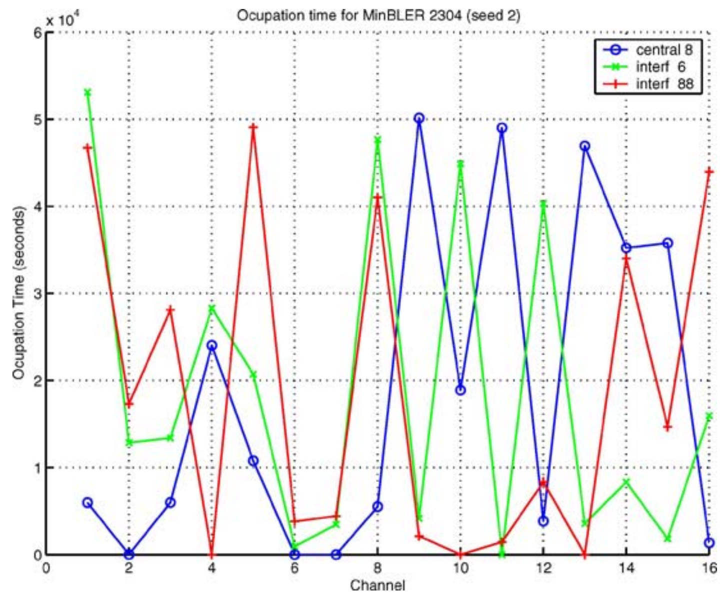

Figure 15. Channel occupancy in cell 8 and its first tiers co-channel interfering cells (minBLER scheme, array size = 2304, single simulation run with seed = 2).

illustrated with channel 11 in Figure 14. Since this channel is not used in cells 24 and 42, its first tiers co-channel interferers (22, 40 and 4) will heavily use it; see Figure 14. This is observed despite the fact that cells 22, 40 and 4 are also second tiers interferers of the central cell (44) and that this cell heavily uses channel 11. As a result, the cooperation among a cell and its first tiers interferers dominates. On the other hand, Figure 14 shows that since cells 60 and 6 do not have an 'interference relation' with cells 24 and 42, the use of channel 11 in such cells will be avoided reducing the interference experienced by the central cell (44) in this channel. If we now look at the channel occupancy pattern of a cell (e.g., cell 8) that is interfered (as a first tiers interferer) by cell 6, we can observe that the use of channel 11 in such cell is quite high; see Figure 15.

Despite the good performance attained with the proposed schemes, the usage of channels 1, 10 and 16 shows that further gains could be achieved if a better cooperation among co-channel interfering cells could be obtained; see Figure 13. After all, it is important to remember that the proposed schemes were not specifically designed to guarantee cooperation among interfering cells but that an implicit cooperation has been achieved due to their basic operation.

In the simulation approach considered, each simulation run corresponds to restarting the whole emulation process from scratch. In terms of the channel assignment process, this is equivalent to reinitializing all the channel arrays and starting the allocations without any knowledge of the channel quality experienced in previous transmissions. In a real system, reinitializing the channel arrays could be easily done at times of low system load, for example during the night[9]. Figure 16 shows that after the channel arrays have been reset, cooperation among co-channel interfering cells is still maintained, although this time the channels that are heavily used in the central cell differ from the ones shown in Figure 13; check for example

[9] In any case, such re-initialization would be a very simple task since it is just a memory erasure.

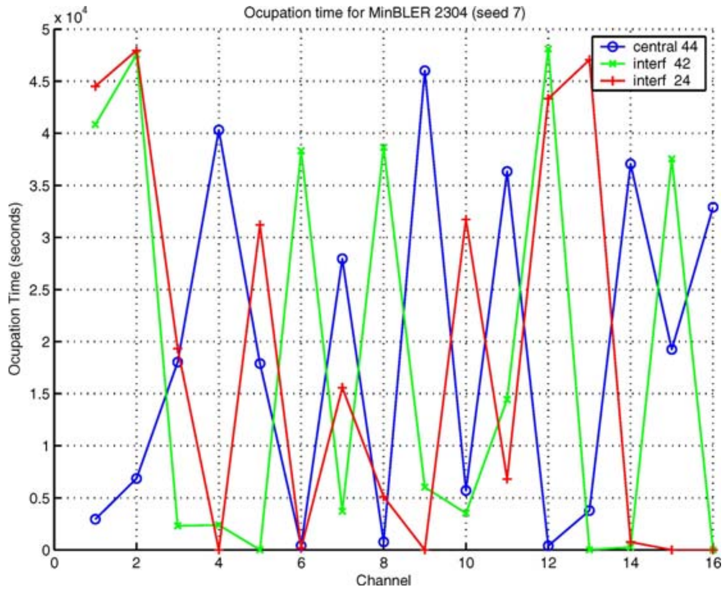

Figure 16. Channel occupancy in cell 44 and its first tiers co-channel interfering cells (minBLER scheme, array size = 2304, single simulation run with seed = 7)

channels 4, 9 and 16. Figure 16 models the same system as Figure 13 but using a different seed for the random number generators. Actually, these two figures prove that the reset of the channel arrays results in that the channels that are heavily used in a given cell and not in its interfering cells change. As it was illustrated in Figure 11, by reinitializing the channel arrays, a long-term channel uniform use that does not overcharge particular channels is then guaranteed.

Figure 17 plots the channel occupancy for the central cell (44) if the channels arrays are not reinitialized.[10] Each subplot corresponds to a different simulation length. For comparison purposes, the results shown in previous sections were obtained performing 10 different simulation runs, with each run emulating 80000 seconds (over 22 hrs) of radio transmission. Figure 17 shows that if the channel arrays are not periodically reinitialized, the long-term channel uniform use would not be guaranteed. According to this figure, the considered simulation length is not an important factor.[11] Table 5 compares the minBLER system performance obtained periodically resetting the channel arrays (performance discussed in the previous section) to that obtained without resetting the arrays (corresponds to the subplots shown in Figure 17). The reported results show that once a channel use pattern such as the one observed in Figure 13 is obtained, not periodically reinitializing the channel arrays, not only does not help avoiding surcharging particular channels but also it does not improve the system performance.

As a result, to realize the full benefit of the proposed schemes, the arrays used to store the channel quality measurements obtained during previous transmissions should be reset

[10] This is equivalent to performing a single simulation run (the simulation lengths considered guarantee a good statistical accuracy of our results) without varying the seed used in the random number generators.

[11] The simulation lengths considered are: 240000 sec (over 66 h), 320000 sec. (over 88 h), 800000 sec (over 222 h or more than 9 days) and 1600000 sec. (over 444 h or more than 18 days). This last value doubles the total simulation length considered to report the results reported in Figure 11 and Section 6.

Table 5. Comparison of the minBLER performance resetting or not the array sizes for different simulation lengths

		Single seed and various simulation lengths (in seconds)			
	All seeds	240000	320000	800000	1600000
Mean throughput (kbits/s)	19.14	19.06	19.12	19.12	19.05
Minimum throughput for 95% of samples (kbits/s)	14.83	14.65	14.75	14.77	14.63
Mean normalized delay (ms/kbit)	67.7	67.9	67.7	67.7	68.0
Highest normalized delay for 95% of samples (ms/kbit)	103	103.3	103	103	103
Average BLER (%)	4.32	4.45	4.35	4.34	4.46
Highest BLER for 95% of samples (%)	10.72	11.06	10.82	10.81	11.10
Average BER (%)	0.39	0.42	0.40	0.39	0.42
Average nb of CS changes per sec.	2.062	2.0947	2.068	2.066	2.102
Optimal CS (%)	78.56	78.04	78.44	78.46	77.89

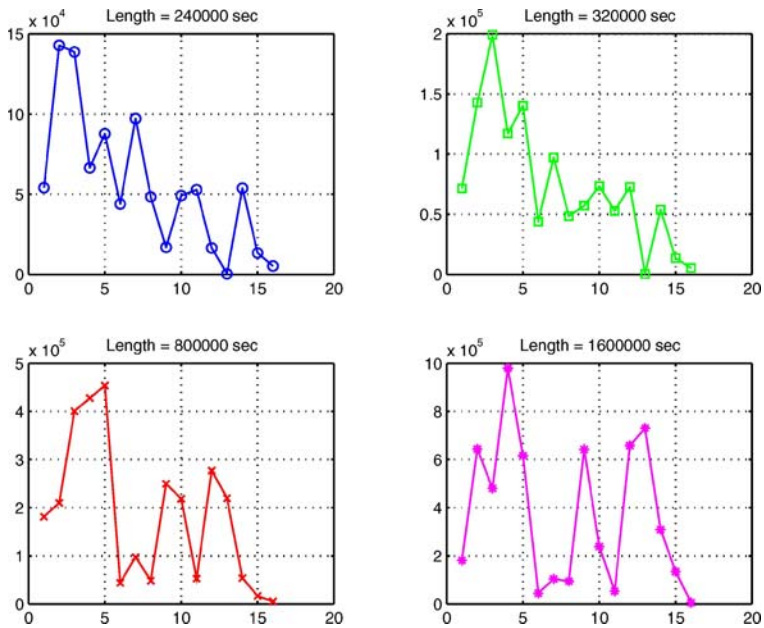

Figure 17. Channel occupancy in cell 44 considering different simulation lengths (minBLER scheme, array size = 2304, single simulation run without resetting arrays).

periodically. This way, the proposed schemes would not only increase the average system performance and improve the QoS for the users experiencing the worse service, but they would also guarantee a long-term channel uniform use.

8. Conclusions

A set of link-level assisted cross-layer channel assignment schemes have been proposed and evaluated in this paper. The proposed schemes assign an incoming call the available channel that experienced the best channel quality conditions during previous transmissions. Three different channel quality metrics have been considered: CIR, BER and BLER. The performance of the proposed schemes has been compared to that obtained considering the commonly used random allocation mechanism. The obtained results show that, compared to the random allocation technique, the proposed schemes improve the system performance and the operation of RRM techniques such as Link Adaptation. The improvement is particularly important for the users experiencing the worse service, thereby highlighting the proposed schemes guarantee a fairer system operation. The scheme achieving the highest performance is the algorithm based on BLER estimates. This is particularly relevant since it is also the scheme with a lower implementation cost. The conducted study has also shown that the performance of the proposed schemes is very sensitive to the size of the channel arrays used to store the channel quality estimates obtained during previous transmissions.

This study has also shown that the proposed schemes guarantee a long-term uniform use of all channels, thereby avoiding the surcharge of particular RF equipments, if the channel arrays are regularly reinitialized. On the other hand, the proposed schemes exhibit a short-term channel use pattern that results in an implicit cooperation among co-channel interfering cells during the channel allocation process. In particular, it has been observed that with the proposed schemes, interfering cells avoid transmitting using the same channels, reducing the experienced interference. This lower interference level is at the origin of the higher system performance obtained with the proposed schemes.

It is also interesting to note that the results reported in this paper have highlighted that a higher system performance could be obtained if the cooperation among interfering cells during the channel assignment process was improved. The authors of this study are actually studying the application of new techniques that could improve such cooperation and therefore further increase the system performance.

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