Resource Allocation for Cellular Radio Systems

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Abstract

High terminal traffic densities are expected in urban multiuser radio systems. An efficient allocation of resources is the key to high system capacity. In this paper a distributed dynamic resource allocation(DDRA) scheme based on local signal and interference measurements is proposed for multi-user radio networks. It offers "soft capacity", for time division multiple access (TDMA) and frequency division multiple access (FDMA) systems, bounded above by N per base station, where N is the total number of channels in the system. The decisions are made local to a terminal and its base and are essentially independent of the rest of the system. A distributed dynamic channel assignment scheme is used to assign channels to new calls. This scheme assigns a channel that offers the maximum carrier to interference ratio (CIR) to a new call. A distributed constrained power control (DCPC) scheme based on CIR measurements is used for power control. The channel assignment scheme and the power control scheme are coupled to obtain an interactive resource allocation scheme.

We compare the capacity of a system which uses the distributed dynamic resource allocation scheme described above with the capacity of a system which uses the channel assignment scheme alone. The system capacity is measured by simulation as the number of terminals that can be served by the system with a CIR above an acceptable minimum. Our results for a one-dimensional cellular system show that coupling the channel assignment scheme with power control offers a

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higher system capacity than when the channel assignment scheme is used alone. Simulations were also used to show the effect of varying the maximum transmitter power on system capacity.

1 Introduction

In multiuser radio networks it is desirable to maintain bit error rates above a chosen minimum. This would require that the carrier to interference ratio(CIR) of the radio links be maintained above a corresponding minimum CIR for the network by assigning channels and transmitter powers to terminals appropriately. The allocation of resources namely channels and transmitter powers to terminals based on signal and interference measurements has been studied extensively independent of each other. Some of the work on channel assignment relevant to this study can be found in ([1] - [8]). Previous work on power control relevant to this study is available in ([9] - [26]). There has been some effort to study the performance of channel assignment and power control together. Capacity analysis and simulations [27] show that dynamic channel assignment and power control together offer high system capacities. Reuse distance based dynamic channel assignment with power control has been studied in [8]. A medium access protocol that combines dynamic channel assignment and a CIR-based power control is presented in [28]. Integration of power control and base assignment presented in [29] also offers higher system capacity.

In this paper we propose a distributed dynamic resource allocation (DDRA) scheme that integrates channel assignment and power control. This scheme was first reported in [30]. The channel assignment couples well with the power control to offer a higher system capacity than just channel assignment by itself. The system capacity is measured by simulation in terms of the number of terminals that can be served by the system with a CIR above a chosen minimum.

2 Models and Performance Measures

In traditional performance analysis of cellular systems, Poisson call arrivals and exponential call durations are assumed. It is also assumed that the cell sizes are large compared to the movement of the terminal during a call.

With these assumptions the system is modeled as a Markovian queueing system with blocking. In microcell systems the calls may have to be carried through a few base stations. A dynamic channel assignment scheme would also require channel reassignments within a cell. If these effects are taken into consideration traditional analysis would become intractable. Therefore, to study the performance of various resource allocation schemes extensive simulation studies are necessary. However, these studies do not offer enough insight into the principles of the resource allocation problem.

In ([4],[8]) a new simplified approach to studying the complex problem of resource allocation is introduced. Here the system is studied at one randomly chosen instant of time. The system frozen in that time instant is referred to as a snapshot. The resource allocation scheme under study is then applied to this snapshot. It is assumed to be infinitely fast, i.e., the resource allocation is allowed to reach its final "state" before the performance is evaluated. The performance is measured by counting the number of terminals that the resource allocation scheme is not able to accommodate. This process is repeated for a number of snapshots and the performance is averaged over all the snapshots. This is referred to as the snapshot analysis. The snapshot analysis is used in this work for evaluating the performance of the resource allocation schemes by simulations. The snapshot analysis does not distinguish between terminals with different types of requests such as, new calls, handoffs, ongoing calls, etc. The snapshot simulations will not replace a full scale system simulation. It cannot for example consider any time correlation properties of the teletraffic, i.e. call arrival and call duration statistics. However, it can be used as a complement when comparing different resource allocation schemes.

Though the resource allocation presented in this work is for two-dimensional cellular systems, we use a one-dimensional cellular system in the simulations to keep the computations simple. The base stations are located at regular intervals. We study the system at a randomly chosen instant of time. The number of terminals in each cell is assumed to be a Poisson distributed random variable with mean λ_c. We let the size of the channel set for the system be denoted by N. The normalized mean traffic is $\lambda \equiv \lambda_c/N$ terminals per channel per cell. The terminal positions are uniformly distributed in each cell. This model with independent and exponentially distributed distances between adjacent cars is known to be a good model for free flowing highway traffic [31]. For other kinds of traffic there are no well known models. We use the above traffic model for the one-dimensional cellular system in the simulations.

We present resource allocation for the uplink (mobile to base) only. For the downlink (base to mobile) the same procedure is valid with appropriate change in notation. The number of terminals using a given channel is denoted by M. We let P_i be the power transmitted by the i^{th} terminal unit. The M dimensional vector $\boldsymbol{P}$, with P_i as its i^{th} element, is the transmitter power vector for the transmitters using a given channel. The gain on the communication link between the i^{th} base and the j^{th} terminal is denoted by G_{ij}. Thus, the G_{ii}'s are the gain factors on the desired communication links, while the G_{ij}'s, for $i \neq j$, represent gain factors on the links that cause interference. All the G_{ij}'s are positive and can take values in the range $(0, 1]$. The link gains are given by $G_{ij} = gd_{ij}^{-\alpha} S_{ij}$, where g is a constant depending on the antenna gains, d_{ij} is the distance between the j^{th} terminal and the i^{th} base station, α is propagation exponent, and S_{ij} is the slow fading factor that is log-normal distributed. If no fading is assumed S_{ij} is unity. In the simulations g is set to unity. The receiver noise at the base station corresponding to the i^{th} terminal is denoted by ν_i. In the simulations the noise is assumed to be the same for all receivers. The link quality is measured by the carrier to interference ratio(CIR). The CIR of the i^{th} terminal at its base is given by

$$\gamma_i = \frac{P_i G_{ii}}{\sum_{\substack{j=1 \\ j \neq i}}^{M} P_j G_{ij} + \nu_i} \ , \ 1 \leq i \leq M \ . \tag{1}$$

Equation (1) for the CIR of the i^{th} terminal at its base can be rewritten as

$$\gamma_i = \frac{P_i}{\sum_{j=1}^{M} A_{ij} P_j + \eta_i} \ , \tag{2}$$

where the $M \times M$ matrix $\boldsymbol{A} = \{A_{ij}\}$ is defined by

$$A_{ij} = \begin{cases} \left(\dfrac{G_{ij}}{G_{ii}} \right) & \text{if } i \neq j \\ 0 & \text{if } i = j \ . \end{cases} \ , \tag{3}$$

and $\eta_i = \nu_i / G_{ii}$. We let $\boldsymbol{\eta}$ be the M dimensional vector whose i^{th} element is η_i. The η_i's are greater than or equal to zero. We assume that at least one of the η_i is not zero if noise is not negligible.

The lowest CIR that is acceptable to the receiver is denoted by γ_f. The CIR floor, γ_f, is a parameter used in the simulations to decide when to remove or deny service to a terminal. The maximum transmitter power for a terminal is denoted by P_{max}.

The performance measure used in the simulations for snapshot analysis is P_a, the probability of assignment failure. It is the probability that a randomly picked terminal suffers an assignment failure. This performance measure was first introduced for snapshots in [4] as the assignment failure rate. $\hat{P}_a$ an estimate of P_a, is obtained as an average over K snapshots of the cellular system. A terminal can suffer an assignment failure in two ways. Firstly when all the channels are already assigned by the base station to other terminals at the time the terminal requests service. Secondly, when a terminal is assigned a channel and transmitter power, it can cause other terminals already on that channel to have a CIR below the CIR floor. The expression for $\hat{P}_a$ is as given below

$$\hat{P}_a = \frac{\sum_{i=1}^{K} \text{number of terminals denied service in snapshot } i}{\sum_{i=1}^{K} \text{number of terminals that need service in snapshot} i}. \tag{4}$$

In the simulations K is large enough so as to have a 95% confidence interval that is acceptably small for the P_a estimate (at least an order of magnitude less than the estimated P_a). An approximate confidence interval is used in the simulations. The probability of an assignment failure is assumed to be Bernoulli. With this assumption the 95% confidence interval is estimated as

$$\hat{P}_a \pm 1.96\sqrt{\hat{P}_a(1-\hat{P}_a)/L} \tag{5}$$

where

$$L = \sum_{i=1}^{K} \text{number of terminals that need service in snapshot} i.$$

This confidence interval will be an upper bound since there is a positive correlation between the number of assignment failures and the number of terminals. It should be noted from Equation 5 that for lower traffic, L, the confidence interval becomes less tight.

Values of $\hat{P}_a$ less than 1×10^{-4} are not of much interest. Moreover they are difficult to estimate with a tight confidence interval (since they require large amounts of data). So in all our plots of $\hat{P}_a$ we show only values greater than 1×10^{-4}.

When an unlimited number of channel reassignments and power control iterations are allowed the measures obtained by the snapshot analysis can be viewed as an upper bound on the traffic load(number of terminals/cell/channel) that can be handled at a certain assignment failure rate[8].

The probability of assignment failure is in a sense more fundamental than the traditionally used blocking probability since it does not relate to specific effects of call duration, terminal mobility, handoff schemes etc, but only to their aggregate effect. P_a can be thought of as a measure of the spectrum packing capability of a resource allocation algorithm. So the snapshot analysis, presently neglecting the problems of implementation, allows comparison of spectrum packing capabilities of resource allocation algorithms.

The resource allocation problem considered in this study can be viewed as follows:

Minimize: P_a
Subject to: finite frequency spectrum
finite transmitter power

The above problem is equivalent to maximizing spectrum packing. The channel assignment part of the above problem makes it a combinatorial optimization problem that is not easily solved. We attempt to solve the above problem, based on heuristics, with a distributed dynamic resource allocation scheme and obtain a suboptimal solution. We are interested in a distributed scheme because of the advantages that it would offer in implementation. With a distributed scheme there is no need for communication amongst base stations, no need for a central controller, and addition of new base stations is easy.

3 Channel Assignment

The channel assignment scheme used here is the well known minimum interference scheme. It is incorporated in the CT-2(Enhanced Cordless Phone) and DECT(Pan-European Cordless Phone) systems. Its performance has been studied in [7]. This scheme is distributed since it is based on local interference power measurements. When a terminal requires service, it signals its need for a channel to the nearest base station. All channels of the system are available for use at each base station rendering the scheme dynamic. The base station measures the interfering signal power on all the channels that it has not already assigned to other terminals. The terminal is then assigned the channel with minimum interference. This can be expressed mathematically as:

A terminal i is assigned a channel that offers a CIR equal to

$$\max_{j \in C}\{\gamma_{i(j)}\},$$

where $\gamma_{i(j)}$ is the CIR of terminal i if it were to use channel j, and C is the set of channels that are not already assigned by the base station to other terminals. Since the terminals are served in a random order (say corresponding to the order of arrival of terminals into a real system) we will refer to this scheme as the random minimum interference (RMI) scheme. A terminal may be denied service in two cases. The first one is when all the channels at the base station are already assigned to other terminals at the time the terminal needs service. The second one is when the terminal suffers a CIR less than γ_f, where γ_f was defined earlier to be the lowest CIR that is acceptable to the receiver.

4 Power control

We use the distributed constrained power control (DCPC) scheme of ([24],[25],[26]) for adjusting transmitter powers in the resource allocation scheme. In this scheme each of the M terminals on a given channel adjusts its transmitter power, so as to achieve a target CIR denoted by γ_t, based on the CIR experienced at the base station. The transmitter power of the i^{th} terminal at the

n^{th} time instant is given by

$$P_i^{(n)} = \min\{P_{max}\ ,\ \gamma_t\ \frac{P_i^{(n-1)}}{\gamma_i^{(n-1)}}\},\ 1 \leq i \leq M\ ,\ n \geq 1\ , \tag{6}$$

where P_{max} is the maximum transmitter power for the system, $P_i^{(n-1)}$ is the transmitter power of the i^{th} terminal at the $(n-1)^{th}$ instant of time, and $\gamma_i^{(n-1)}$ is the corresponding CIR of the i^{th} terminal at the base station at the $(n-1)^{th}$ instant of time. The above scheme is shown to converge for any arbitrary initial power vector ([24],[25],[26]). Whether the power updates of the terminals are synchronous or asynchronous, the above scheme converges to the same power vector in the limit when $n \to \infty$. We shall refer to the above power control scheme as synchronous DCPC(SDCPC) when the power updates of the terminals are synchronous, and asynchronous DCPC(ADCPC) when the power updates of the terminals are asynchronous.

5 The DDRA Scheme

We now propose a DDRA scheme derived by fusing the DDCA scheme described in Section 3 and the DCPC scheme described in Section 4. When a terminal requires service it initially communicates with the base station on the control channel. The base station then assigns a channel that has minimum interference or equivalently a channel that offers maximum CIR. With the knowledge of the interference on the channel and the received signal strength on the control channel, the base station estimates (assuming the link gain on the control channel and the channel assigned to the terminal to be identical) the CIR corresponding to a transmitter power of unity. Using this information the transmitter power necessary to achieve the target CIR is calculated and communicated to the mobile on the control channel. The terminal then joins the rest of the terminals on the same channel in updating powers according to DCPC.

The DDRA scheme: A terminal i that needs service is first assigned a channel that offers

$$\max_{j \in C}\{\gamma_{i(j)}\},$$

where $\gamma_{i(j)}$ is the CIR of terminal i if it were to use channel j, and C is the set of channels that are not already assigned by the base station to other terminals.

The terminal is then assigned a power P_i given by

$$P_i = \min\{P_{max} \ , \ \gamma_t \ \frac{1}{\gamma_i}\},$$

where γ_i is calculated with the interference measured on the assigned channel and the received power assuming unit transmitter power(this can be estimated by using received signal strength measurements on the control channel). The terminal i then joins the rest of the terminals on the assigned channel in adjusting transmitter powers according to the DCPC scheme (synchronous or totally asynchronous) of Section 4.

A terminal can suffer an assignment failure in two ways. Firstly when all the channels are already assigned by the base station to other terminals at the time the terminal requests service. Secondly when the terminal that is already in service suffers a CIR less than γ_f. The terminals are served in a random order (say corresponding to the order of arrival of terminals in a real system).

It is desirable to set γ_t to a value greater than but close to γ_f in order to keep the transmitter power levels small.

6 Choice of P_{max}

Choosing high values of P_{max} will make receiver noise power negligible and give a larger dynamic range. This will translate into more terminals supported with higher CIRs and lower P_a. However choosing low values of P_{max} will conserve power, reduce interference to other systems, and keep radiation levels low.

The measure of radio link quality is the CIR. We reproduce (for our convenience) Equation (1) below which gives the expression for the CIR of the i^{th} terminal at its base.

$$\gamma_i = \frac{P_i G_{ii}}{\sum_{\substack{j=1 \\ j \neq i}}^{M} P_j G_{ij} + \nu_i} \ , \ 1 \leq i \leq M \ . \tag{7}$$

To understand how P_{max} is related to other cell parameters let us consider the worst case CIR. Let γ_w denote the worst case CIR experienced in the system. A lower bound for γ_w is given by

$$\gamma_w = \frac{P_{max} G_w}{I_w + \nu} \tag{8}$$

where G_w is the worst case link gain in the system, I_w is the worst case interference in the system, and ν is the receiver noise. Note that G_w is less than unity and is dependent on cell size and propagation exponent, among other factors. I_w is dependent on cell size, propagation exponent, and also on P_{max}, among other factors. Outage would result when $\gamma_w < \gamma_f$. So we would like $\gamma_w \geq \gamma_f$. Let us assume that P_{max} is chosen such that $\frac{P_{max} G_w}{\nu}$ is about 20dB. This will ensure full radio signal coverage in a cell and make the system interference limited (i.e. receiver noise becomes negligible). Higher values of P_{max} will not offer any significant gain in capacity, and will only result in high radiation levels. This is because the repercussion of using a high P_{max} will be felt in the interference I_w which originates from other interfering transmitters. To some extent efficient DCA and power control help in keeping interference low. Thus the choice of P_{max} in cellular system design is typically based on the average propagation loss experienced in the cells and the receiver noise.

7 MAXMIN Scheme

The MAXMIN scheme is a non-distributed dynamic channel assignment scheme, proposed in [7], as a way of obtaining a bound on the capacity that can be achieved by channel assignment schemes based on interference measurement. In the MAXMIN scheme a terminal is assigned a channel that maximizes the minimum of the CIRs of all the terminals that are being served by the system at that time. Mathematically this can be expressed as:

A given terminal that requires service is assigned a channel j that gives

$$\max_{j \in C} \min_{i \in S} \{\gamma_i\} \tag{9}$$

for the system, where i and j are the indices for terminals and channels respectively. C is the set of channels available at the base corresponding to the given terminal that requires service. γ_i is the CIR of terminal i at its base station. The set S consists of all terminals in the system that are already in service and also the given terminal that requires service. Furthermore in a one-dimensional cellular system (as is the case in our simulations) the left to right order of terminal positions can be exploited to assign frequencies efficiently. A terminal is served only after all terminals to the left of it have had a chance to be served. This sequential left to right order of service is chosen because it appears to be the best way of reusing channels. The terminal that is immediately to the right of a given set of terminals with channels assigned is the one that will cause the most interference at the base stations serving the given set of terminals. It is also the one that suffers the most interference from that set of terminals.

8 Simulation Results

In this section we present simulation results for the DDRA scheme. In the simulations we consider only the propagation loss on the radio links. So we assume that $G_{ij} = d_{ij}^{-4}$, where d_{ij} is the distance between the i^{th} base and the j^{th} terminal.

The RMI and DDRA schemes are applied to a one-dimensional cellular system with 50 cells. γ_f for the system is chosen to be 15.89 dB. Two cases of the DDRA scheme are studied. One uses synchronous DCPC and is referred to as the DDRA-SDCPC scheme. The other uses asynchronous DCPC and is referred to as the DDRA-ADCPC scheme. In the DDRA scheme after a terminal is assigned a channel 5 iterations(SDCPC) or 5 cycles(ADCPC) of power control are performed before the next terminal is served. A cycle is an ordered set of updates with one update from each terminal. We use cycles of updates for ADCPC to keep the simulation simple. Note that ADCPC can actually have totally asynchronous updates ([24],[25],[26]). γ_t for power control is set 3 dB higher than γ_f. The maximum transmitter power was set to 1W and the receiver noise power was assumed to be 10^{-10}W. The statistics are taken from only the inner 20 cells to avoid boundary effects. The cells are all of the same size and equal to 100m. The base station is located at the center of each cell. The number of terminals in each cell is a Poisson random variable with mean λ_c. If N denotes the size of the channel set for the system, then $\lambda \equiv \lambda_c/N$ is the mean traffic per cell per channel. The terminals are frozen in their positions and served in a random order. In both the RMI scheme and the DDRA scheme the terminals are denied service if on their turn of service all the channels at the base station are already assigned. In the RMI scheme the terminals that are assigned channels are denied service if their CIR falls below γ_f. In the DDRA scheme the terminals that are already assigned channels are denied service if they suffer a CIR less than γ_f after any iteration(SDCPC) or cycle(ADCPC) of power control. The performance measure P_a is obtained as an average over a number of snapshots of the system. In Figure 1, P_a is plotted for $N = 5$ as a function of the normalized mean traffic λ. The same curves are plotted in Figures 2 and 3, for $N = 10$ and $N = 20$ respectively. In all the three figures we see an improvement in system performance with the DDRA scheme over the RMI scheme. The difference in the performance of the DDRA-SDCPC and DDRA-ADCPC is due to the fact that only five power updates are carried out in between two new service requests.

In Fig. 3 the performance curve for the MAXMIN channel assignment scheme is plotted. Note that the MAXMIN scheme also tries to balance the CIRs as best as the discrete resource (namely channels) allows. We can see from Fig. 3 that it performs better than the DDRA scheme. From this we gain insight into the importance of the channel assignment scheme that is combined with power control. The capacity offered by resource allocation using power control depends on the spectrum packing capability of the underlying channel assignment scheme. With FCA, power control does not offer any capacity gain because the capacity of FCA is limited by the number of channels at the base. Combining a dynamic channel assignment scheme such as RMI with power control offers significant capacity. Even this capacity can be stretched further as indicated by the MAXMIN scheme in Fig. 3. The capacity of the resource allocation scheme could be increased by using a more efficient channel assignment scheme than RMI. Fig. 4 gives a summary of the resource allocation schemes compared in the simulations.

We next investigate the importance of P_{max} in system design. In Fig. 5, P_a for the DDRA-SDCPC scheme in a system with $N = 10$ channels, is plotted as a function of the maximum transmitter power P_{max}, for λ =0.3 and 0.4. The cell size is 100m. The noise power was assumed to be 10^{-10}W. In reality the noise power is typically in the range of 10^{-15}W. We can perform a scaling operation to reflect this fact while keeping the CIRs the same. In the simulations the CIR, γ_i of the i^{th} terminal is given by

$$\gamma_i = \frac{P_i d_{ii}^{-4}}{\sum_{j \neq i} P_j d_{ij}^{-4} + \nu} \tag{10}$$

where ν is the noise power and is set to 10^{-10}W. Multiplying the numerator and denominator of the right hand side of Equation (10) by 10^{-5} we get

$$\gamma_i = \frac{P_i d_{ii}^{-4} 10^{-5}}{\sum_{j \neq i} P_j d_{ij}^{-4} 10^{-5} + \nu 10^{-5}}$$

or

$$\gamma_i = \frac{P_i (d_{ii} 10^{1.25})^{-4}}{\sum_{j \neq i} P_j (d_{ij} 10^{1.25})^{-4} + 10^{-15}}.$$

So while keeping the CIRs the same as before we have performed a scaling operation to reflect a noise power level of 10^{-15} corresponding to a new cell size of 1778.28 m (i.e. $100m \times 10^{1.25}$). We can see in Fig. 5 that for P_{max} less than 10mW noise predominates and assignment failures are mainly due to inadequate signal level to overcome receiver noise. However for P_{max} greater than 100mW noise is negligible (i.e. the system is interference limited) and assignment failures are mainly due to traffic overload. We see that increasing P_{max} beyond 100mW does not offer significant improvement in performance. The worst case link gain G_w (refer to Section 6) in the simulation is $(1778.28/2)^{-4}$ and the corresponding noise power, ν is 10^{-15}W. So we have for $P_{max} = 100mW$, $\frac{P_{max} G_w}{\nu}$ =22.04 dB. From the discussion above we see that once noise is negligible the dynamic range of power does not offer much gain. This is in agreement with the fact observed in [21] that increasing dynamic range of transmitter power beyond a certain value for a noiseless system does not offer a substantial increase in capacity. As mentioned in Section 6, typically P_{max} is chosen based on the average propagation loss experienced in the cells and the receiver noise.

9 Conclusions

In this paper a distributed dynamic resource allocation scheme based on signal and interference measurements is proposed. It offers "soft capacity" for TDMA/FDMA systems up to a maximum of N users per base station, where N is the total number of channels in the system. The scheme is derived by fusing a channel assignment scheme and a power control scheme that couple well. It is shown by simulations, for one-dimensional cellular systems, that the DDRA scheme offers a higher system capacity than the distributed dynamic channel assignment scheme operating alone.

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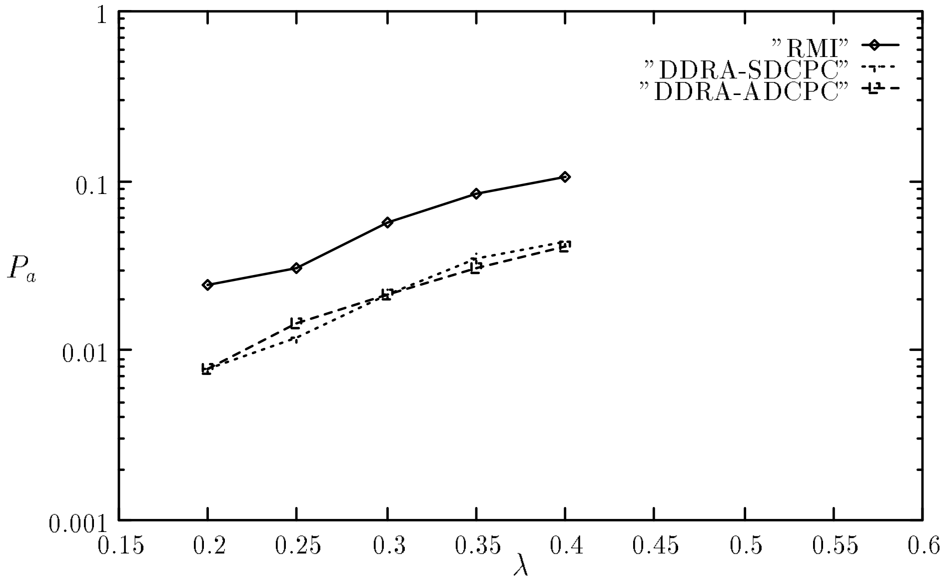

Figure 1: Probability of assignment failure P_a as a function of the normalized mean traffic λ terminals/cell/channel, for $N = 5$ channels in the system.

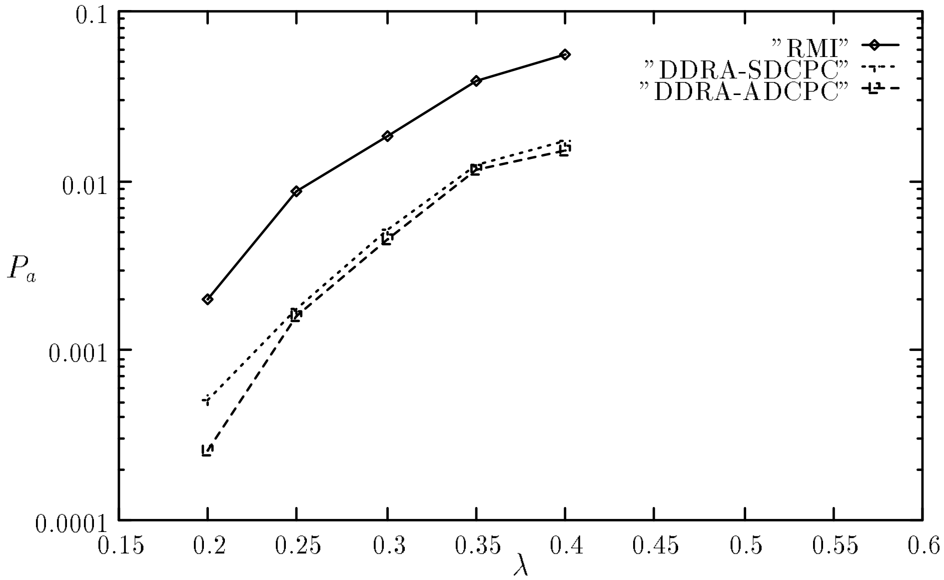

Figure 2: Probability of assignment failure P_a as a function of the normalized mean traffic λ terminals/cell/channel, for $N = 10$ channels in the system.

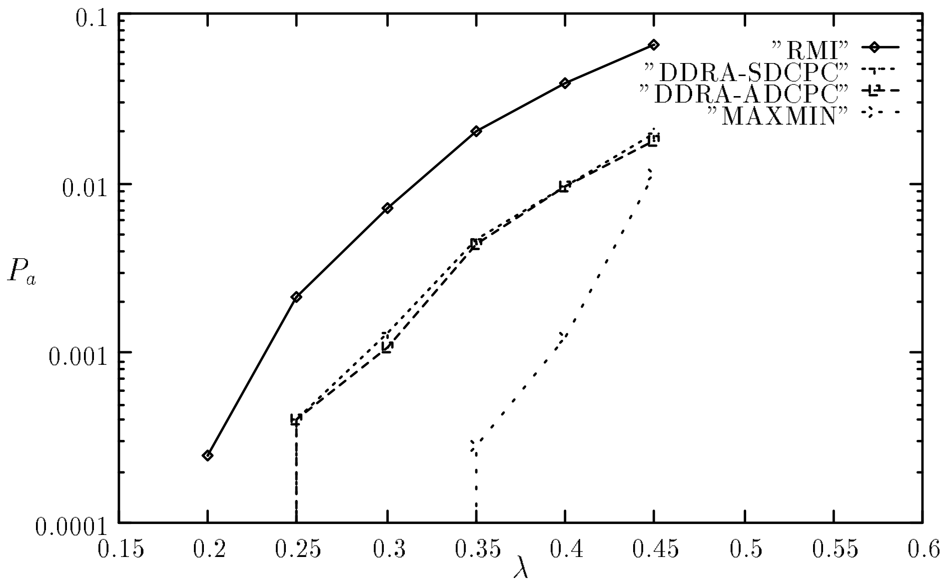

Figure 3: Probability of assignment failure P_a as a function of the normalized mean traffic λ terminals/cell/channel, for $N = 20$ channels in the system.

Scheme (Ordered by decreasing P_a)	Description	Components	
		Power Control	Channel Assignment
RMI	Random Minimum Interference	None	RMI
DDRA	Resource Allocation	SDCPC or ADCPC	RMI
MAXMIN	Maximum Minimum CIR	None	MAXMIN

Figure 4: Summary of the resource allocation schemes compared in the simulations.

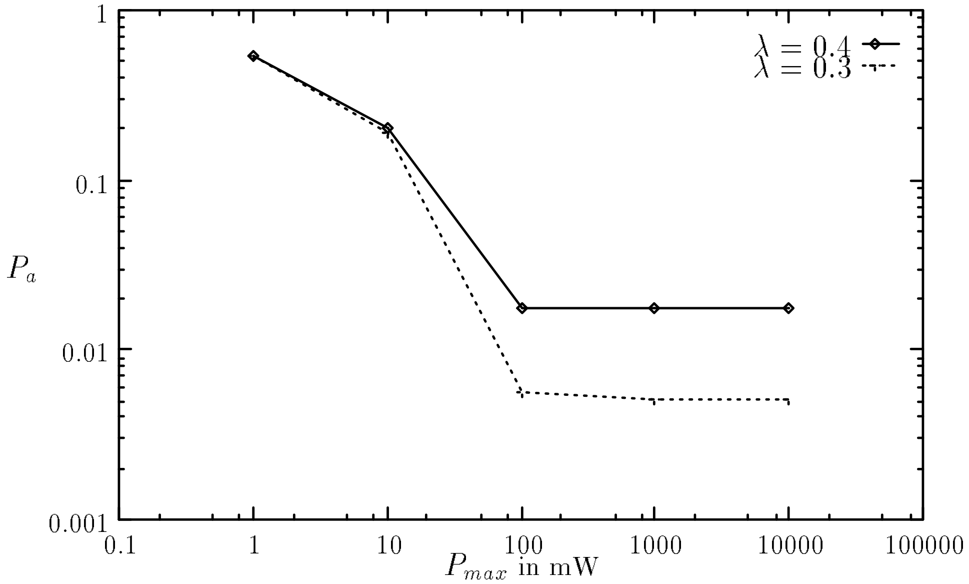

Figure 5: Probability of assignment failure P_a for the DDRA-SDCPC scheme as a function of the maximum transmitter power P_{max}, for $N = 10$ channels in the system. The receiver noise is assumed to be 10^{-10}W. The two curves correspond to $\lambda = 0.3$ and 0.4 terminals/cell/channel.