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Carrier Assignment Algorithms in Wireless Broadband Networks with Channel Adaptation

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Carrier Assignment Algorithms in Wireless Broadband Networks with Channel Adaptation

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Abstract— **Wireless broadband access is an appealing solution to the projected trend towards reliable and easily deployable high-speed connections. In order to enhance system capacity and tolerate volatility of the wireless medium, sophisticated adaptation techniques are required. In this paper, we consider the problem of efficient resource allocation with adaptive modulation techniques in a multi-carrier wireless cellular system. We identify the inherent complexity of the problem and propose a heuristic algorithm for carrier frequency assignment to users, based on channel quality. The algorithm leads to an efficient allocation, in the sense that each user is assigned to a carrier and occupies the least number of channels (timeslots). Simulation results show that the algorithm leads to high link utilization and low blocking rate for a wide range of traffic loads and interference levels.**

Keywords— **Wireless broadband networks, carrier frequency allocation, adaptive modulation.**

I. Introduction

The projected trend towards reliable high-speed connections has increased the need for broadband access and services. While a lot of attention has been devoted to wireline broadband access techniques, such as xDSL and cable modems, fixed wireless broadband networks appear as an appealing solution for both service providers and end-users, due to flexibility, easiness of deployment and fast flow of revenues. The ability to support high data rates in a wireless environment depends on aggressive spectrum reuse and use of efficient multiple access schemes. The former guarantees achievability of high rates, while the latter results in efficient resource allocation and mitigation of channel impairments. Currently envisioned wireless access schemes are based on the principle of multi-carrier transmission, also known as Orthogonal Frequency Division Multiple Access (OFDMA). This has been proposed as a means of achieving high data rates in several next generation wireless standards [1]. In OFDMA, spectrum is divided into multiple orthogonal narrowband subchannels (subcarriers) and information symbols are transmitted in parallel over these low-rate subchannels. Intersymbol interference (ISI) and multipath delay spread are reduced, and thus attainable data rates are increased.

In wireless broadband networks, sophisticated resource management and reuse are required. Given a set of users with certain requirements, an efficient algorithm should try to minimize the number of channels needed to satisfy user requirements at every instant, so that the system can respond better to a sudden traffic increase or link deterioration. However, wireless channel impairments and interference impose constraints on resource reuse and data rate achievability, since the signal-to-interference-and-noise ratio (SINR) must be maintained at an acceptable level. The main idea in [2] is to identify and minimize the major sources of interference with the Staggered Resource Allocation (SRA) algorithm.

Adaptive transmission methods provide the potential to adjust modulation level and symbol rate, so as to ensure an acceptable bit error rate (BER). Although high modulation levels and symbol rates provide high throughput, they are more susceptible to interference and multipath delay spread respectively. In [3], the best combination of modulation level and symbol rate is derived from feedback measurements of interference and delay spread. Thus, high modulation levels are assigned to users in good quality channels to increase throughput, while lower modulation levels are more robust to interference and are assigned to users in poor quality channels. A first attempt to consider timeslot allocation with adaptive modulation was reported in [4]. A systematic study of resource allocation with adaptation of modulation level and transmission power with the objective to maximize throughput per utilized channel is presented in [5] for different multiple access schemes with orthogonal channels.

Different users perceive different channel quality, based on their location. In a multi-carrier system, resource allocation comprises the assignment of carrier frequencies to users. Each user occupies different number of channels in different carriers, depending on individual channel quality in a carrier. With an appropriate assignment strategy and modulation level control, each user can be assigned to a carrier, so that the number of occupied channels is reduced. We address the problem of efficient carrier allocation with modulation level adaptation, so as to improve multi-carrier transmission and enhance system capacity. We identify the intractability of the problem and propose the Best Carrier Selection (BCS) algorithm, which results in efficient carrier assignment, in the sense that each user selects the carrier that leads to reduced number of occupied channels.

The paper is organized as follows. In section II we provide the model and in section III we describe an algorithm for carrier allocation with adaptive modulation. In section IV we elaborate on this problem for splittable or non-splittable user requirements among carriers. Numerical results are presented in section IV. Finally section V concludes our study.

II. System Model

Consider a wireless cellular network and focus on base station i, which covers to a cell with M users. System resources consist of a set of carrier frequencies $\mathcal{F} = \{1, 2, \ldots, N\}$, which are available in all cells. Each carrier frame has duration T_f and is divided in orthogonal timeslots, each of which is a channel. Users of the same base use distinct channels. Perfect synchronization is assumed among carriers of the same base and among carriers of different bases.

Let $\mathcal{B}$ denote the set of bases surrounding base i. Path loss coefficients G_{ij} between base i and user j are provided. They characterize completely the propagation environment, in the sense that when base i transmits power P_i, user j receives power $G_{ij}P_i$. A user j receives interference I_j from neighboring bases that transmit in the same channel. The SINR for user j in cell i is

$$W_j = \frac{G_{ij}}{\sum_{n\in\mathcal{B}:n\neq i} G_{nj}} \, . \tag{1}$$

Each user j has bit rate requirements r_j (in bits/sec), which must be satisfied by resource allocation. These are translated in a number x_j of bits in a frame, so that $x_j = r_j T_f$. We assume that x_j is known. Each user j is assigned to a carrier $k \in \mathcal{F}$. To achieve rate requirements, the user is assigned some channels (slots) n_j^k, a modulation level b_j (bits/symbol) and a symbol rate s_j (symbols/sec) for transmission. These parameters are selected from finite sets of available constellations and symbol rates respectively. Depending on implementation complexity, one or different modulation levels and symbol rates can be assigned in different channels of a user. We assume that a fixed number of symbols, K, are transmitted in a slot. Thus, symbol rate is constant, so that symbol rate adaptation is not an issue. When modulation level b_j is fixed for all n_j^k channels of user j, we have $r_j = K\frac{1}{T_f} b_j n_j^k$, whereas when different modulation levels are used, we have $r_j = K\frac{1}{T_f}\sum_{\ell=1}^{L} b_\ell \cdot n_{j,\ell}^k$, where $n_{j,\ell}^k$ is the number of slots of user j with modulation level b_ℓ in carrier k and L is the number of available constellations. In order to maintain a constant BER regardless of channel quality, different modulation levels are used for different SINRs. Each modulation level b_m has different amount of robustness to interference and therefore it can be mapped to a threshold γ_m through an one-to-one strictly increasing function f, so that $\gamma_m = f(b_m)$. Higher modulation levels are more sensitive to interference and are mapped to higher SINR thresholds.

III. The Best Carrier Selection (BCS) Algorithm

A. Problem statement

A carrier k and a number of channels (slots) within k are assigned to each user j. The number of occupied channels depends on assigned modulation level and symbol rate. Each user perceives different channel quality in different slots and carriers due to interference and frequency-selective multipath fading. Assuming that carrier frequencies occupy a contiguous part of spectrum, the effect of multipath fading and induced delay spread is similar across carriers. A single symbol rate with delay spread immunity for all users is used. Thus, the quality of a carrier is a function of interference conditions, which depend on channel reuse in other base stations.

Cochannel interference for a user is related to distance from serving and neighboring bases. The amount of tolerable cochannel interference depends on the SINR threshold γ_m, i.e on modulation level b_m. The number of occupied channels by a user also depends on the modulation level. When a high modulation level is assigned in a channel, throughput is increased, since more bits are transmitted. Thus, a user requires fewer channels to fulfil requirements and system capacity is increased, since more users can be accomodated. However, high modulation levels are more susceptible to interference and do not allow high channel reuse.

Clearly, each user should be assigned to the carrier which entails utilization of minimum number of channels. However, preferable carriers may be overloaded or unavailable. In that case, lower quality carriers must be utilized, to the expense that more slots (i.e bandwidth) will be utilized to fulfil user requirements. The arising problem is the following: Given a set of users with some rate requirements and given the interference level at each channel within each carrier, allocate carriers and timeslots to users, so that each user is assigned to the carrier which results in minimum bandwidth utilization. The problem of optimal carrier assignment pertains to identifying an allocation of users to carriers such that minimum number of channels (or minimum number of carriers) is used. We assume that user requirements are not splittable among carriers, namely a user is assigned to one carrier.

B. Description of the proposed algorithm

We present the Best Carrier Selection (BCS) heuristic algorithm, which allocates each user to the most preferable carrier, in terms of channel occupancy. Each user senses the interference level of each channel in each carrier and estimates the bandwidth (number of channels) needed in each carrier to fulfil requirements. Bandwidth estimation is performed by adjusting modulation level in each channel, so that acceptable SINR level is reached. Based on this procedure, each user creates a preference list of carriers. Each user is initially assigned to the most preferable carrier, in the sense that the occupied bandwidth by the user is minimal. If most preferable carriers are overloaded, users should be transferred to less preferable carriers, *so that the additional utilized bandwidth is minimal.* The initial evaluation of carrier k is performed by a greedy procedure, in which a user computes the maximum achievable modulation level in a channel. Channels are assigned one by one to the user, starting with the maximum modulation level ones, until rate requirements are satisfied. Then, user j computes a preference factor C_j^k, equal to the required number of channels in carrier k and creates a preference list $L_j = \left[C_j^1, C_j^2, \ldots, C_j^N\right]$, where $C_j^i \leq C_j^{i+1}$, for $i = 1, \ldots, N-1$.

Each user j is initially allocated to the first carrier in its preference list and a number of slots is assigned. However, since initial carrier estimation is performed independently for each user, several channels in a carrier will be occupied by more than one users. Since users in the same cell cannot use the same channel, channel rearrangement is required. Cochannel users must be moved to an empty channel in the carrier and maintain the modulation level. The order in which cochannel users are rearranged is not important, since the total achieved throughput per carrier will be the same. The rearrangement terminates if all channels in the carrier are occupied by at least one user. If there are channels with more than one users, the carrier is *overloaded*.

Fix attention to carriers k and ℓ, one of which is overloaded after channel rearrangement. Users should be transferred from the overloaded (and most preferable) carrier to the unloaded (and less preferable) one, if there is sufficient capacity in the latter. Users must be transferred so as to induce the minimum increase in bandwidth occupancy. For each user j in carrier k and pair of carriers k and ℓ, we construct a *User-Carrier Transfer Factor* (UCTF) with respect to the tentative transfer of user j from carrier k to ℓ as follows,

$$\Lambda_j\left(k \rightarrow \ell\right) = \frac{C_j^{\ell}}{C_j^{k}}\,, \tag{2}$$

with $\Lambda_j\left(k \rightarrow \ell\right) \geq 1$. This factor captures the transfer "efficiency". Among all candidate users, we transfer the one that causes the minimum inefficiency, i.e. the minimum additional increase in bandwidth. Therefore user transfers having small UCTF take place first. Ties are broken by index assignment to each user. A feasible solution to the problem is an assignment of each user to a carrier, such that all user requirements are satisfied and no carrier is overloaded.

C. BCS Algorithm : Case with two or more carriers

We first study the case of two carriers k and ℓ. If after initial carrier assignment and channel rearrangement both carriers are not overloaded, this is the optimal assignment, whereas if both carriers are overloaded, a feasible assignment does not exist. Assume that carrier k is overloaded and ℓ is not. The idea is to select user j_0 in carrier k, such that,

$$j_0 = \arg\min_j \Lambda_j\left(k \rightarrow \ell\right)\ , \tag{3}$$

and transfer it to ℓ. Channel rearrangement is then performed, since some channels of j_0 in k may become free and some channels of j_0 in ℓ may be occupied by many users. Transfers are performed until both carriers are non-overloaded or overloaded. In the former case we have a solution and in the latter case a feasible solution does not exist.

Consider now the general case with $N > 2$ carriers. If after initial assignment and channel rearrangement no carrier is full, this is the optimal solution, while if all N carriers are overloaded, a feasible solution does not exist. Assume that there are $N' < N$ overloaded carriers. If $N' = 1$, we start moving users from the overloaded carrier (say k) to non-overloaded ones. In that case we must select user j_0 in the overloaded carrier and tranfer it to an appropriate non-overloaded destination carrier ℓ_0, such that

$$(j_0, \ell_0) = \arg\min_{j,\ell} \Lambda_j\left(k \rightarrow \ell\right)\ . \tag{4}$$

If $N' > 1$, there are several overloaded carriers. We select a user j_0 in an overloaded carrier k_0 and move it to a non-overloaded carrier ℓ_0, so that the minimum increase in bandwidth is incurred, i.e we select (j_0, k_0, ℓ_0), such that

$$(j_0, k_0, \ell_0) = \arg\min_{j,k,\ell} \Lambda_j\left(k \rightarrow \ell\right)\ . \tag{5}$$

The algorithm in the general case is outlined as follows.

- **STEP 1** : Compute initial UITF values.
- **STEP 2** : Assign each user independently to best carrier and perform channel rearrangement.
- **STEP 3.A** : If no carrier is overloaded, this is the optimal assignment.
- **STEP 3.B** : If all N carriers are overloaded, there does not exist a feasible assignment.
- **STEP 3.C** : If $N' < N$ carriers are overloaded, transfer user j_0 from carrier k_0 to ℓ_0.
- **STEP 4** : Rearrange channels in carriers k_0 and ℓ_0 .
- **STEP 5**: Update UCTF values for user j_0. Go to Step 3.

IV. Two Versions of the problem

A. Non-splittable user requirements

Assume that user requirements are not splittable among carriers, i.e. a user occupies channels of one carrier. The problem is to find an allocation of M users to N carriers, so that the minimum number of carriers is used. The decision version of the problem is to find if M users can be accomodated in N carriers. This problem is not of polynomial complexity. To understand this, call each user i an "item" and let rate requirements x_i, in bits/frame, be the "size" of the item. Each carrier has a finite "capacity" C_i, equal to the total number of bits that can be supported in a frame, given the interference level at each slot. Each carrier can thus be perceived as a bin of size C_i. Then, the problem of finding if there exists a feasible allocation of M users in N carriers reduces to the *Bin Packing* problem: "Given M items, each with size x_i and an integer N, can we pack the items into N bins?". Bin Packing is NP-Complete. The problem of accomodating M users in the minimum number of carriers is equivalent to minimum Bin Packing, i.e. packing M items in the minimum number of bins, which is NP-Hard [6].

A different version of the problem is to consider the number of channels that the user will occupy in a carrier. We assume that the exact number of channels occupied by a user in a carrier has been determined a priori, after modulation level and channel allocation. The "size" of each item depends now on the carrier in which it is allocated. Therefore, the equivalence with bin packing is not straightforward. Consider the case of M users and $N = 2$ carriers, each with C slots. User i occupies α_i channels if allocated to carrier 1 and β_i if allocated to carrier 2. The problem can be transformed to standard bin packing with two bins, one with capacity C and the other with capacity $C + \sum_i \left(\beta_i - \alpha_i\right)$. In the case of a system with one modulation level, user i utilizes the same number of channels α_i irrespective of carrier and relevance with bin packing follows trivially, for any number of carriers.

B. Splittable user requirements

Assume now that user requirements are splittable among carriers, i.e a user can be assigned to more than one carrier to fulfil rate requirements. In this context, a different problem formulation is the allocation of users to carriers, so that the minimum number of channels in carriers is occupied.

Consider the case of $N = 2$ carriers, each with C slots. Assume that user i occupies α_i and β_i channels if allocated to carrier 1 or 2 respectively. The problem is to find the fraction y_i of i's request that is assigned to carrier 1, so that the total number of channels in both carriers by all users in minimized. The problem can be formally stated as follows:

$$\text{minimize} \sum_{i=1}^{M} y_i \cdot \alpha_i + (1 - y_i)\, \beta_i \ , \tag{6}$$

subject to capacity constraints

$$\sum_{i=1}^{M} y_i \cdot \alpha_i \leq C \quad \text{and} \quad \sum_{i=1}^{M} (1 - y_i)\, \beta_i \leq C \ , \tag{7}$$

and also that $0 \leq y_i \leq 1$, for $i = 1, \ldots, M$. Objective (6) can be written as $\sum_{i=1}^{M} \beta_i + \sum_{i=1}^{M} y_i\, (\alpha_i - \beta_i)$. Observe that coefficients y_i are such that, when $\alpha_i > \beta_i$, y_i should be close to 0 and when $\alpha_i < \beta_i$, y_i should be close to 1.

Each user is initially allocated to the best carrier. If capacity constraints are satisfied, this is the optimal solution. If both constraints are not satisfied, the problem is infeasible. If one of the two constraints is satisfied, users are transferred from the overloaded carrier to the other, so as to induce the minimum increase in number of utilized channels. This is captured by ratios α_i/β_i or β_i/α_i for each user i, depending on satisfiability of constraints. For example, if the first constraint is satisfied and the second is not, users are transferred from carrier 1 to carrier 2 in increasing order of ratios β_i/α_i, until both constraints are satisfied. It is implicitly assumed that a feasible allocation of slots within a carrier can be determined through e.g. power control.

V. NUMERICAL RESULTS

We consider 9 cells arranged in a 3×3 layout and focus on the central cell, which is surrounded by 8 cells. Users are located in fixed but random positions, uniformly distributed in the cell. The distance between base stations in the same row or column is 2 km. System resources consist of 10 carriers, which are available in all cells. Each carrier is divided in timeslots and each user is assigned to only one carrier. The propagation model assumes operation in a suburban environment and considers path loss and shadowing. The received signal (in dB) at distance d from the base station is $L(d) = L(d_0) + 10\kappa \log{(d/d_0)}$, where $d_0 = 10\, m$ is a reference point in measurements ($L(d_0) = 0$ dB) and $\kappa = 4$ is the path loss exponent. Shadow fading for each user is modeled as an independent log-normal random variable with standard deviation $\sigma = 10$dB, while multipath fading is not simulated.

A target BER of 10^{-3} is assumed for users. For an M-QAM constellation in AWGN environment, the BER performance is approximated by

$$BER = 0.2 \exp^{[-1.5\gamma/(M-1)]} \ , \tag{8}$$

where γ is the SINR. Therefore the minimum SINR value for modulation level M is obtained as

$$\gamma = -\frac{M-1}{1.5} \ln{(5\, BER)} \ . \tag{9}$$

This relation determines the SINR threshold for a modulation level. Cohannel interference level depends on channel occupancy in neighboring bases, as well as path loss and shadowing. Results were obtained by averaging over several random experiments. The performance of BCS algorithm is compared with the following schemes:

- BCS algorithm with no user tranfer between carriers. This is the proposed algorithm in section III, but users are not transferred, once they are assigned to the best carrier.
- Least Loaded Carrier (LLC) algorithm. Each user is allocated to the carrier with the minimum load, i.e. the maximum number of free channels.

The performance criteria are the following:

- The blocking ratio P_b, defined as,

$$P_b = \frac{\text{unsuccessfully allocated user bits in channels}}{\text{total number of user bits for assignment}} \ , \tag{10}$$

where a partially accomodated user in a carrier is counted as blocked. Equivalently, the quantity $1 - P_b$ can be perceived as the average *throughput efficiency* of the assignment.

- The link (carrier) utilization U, defined as,

$$U = \frac{\text{total throughput for users and channels}}{\text{maximum total achievable throughput}} \ , \tag{11}$$

where the maximum achievable throughput corresponds to the case when each user is allocated to the best carrier.

We first consider a static situation, where a set of users must be assigned to carriers. Figure 1 illustrates the blocking ratio as a function of severity of interference, which is captured by average channel SINR. We observe that the BCS algorithm alleviates the effect of interference and blocking ratio is low. Thus, for an average SINR of 12 dB, blocking ratio for BCS is reduced by approximately 40%, as compared to the LLC allocation, where interference is not considered. BCS algorithm is particularly effective for moderate interference conditions and is robust for increased interference. Note that the important feature of BCS algorithm is the reassignment of users in non-overloaded carriers.

In Figure 2 the performance of carrier allocation is evaluated in terms of link utilization. BCS algorithm results in high link utilization, since it uses the maximum channel throughput, by modulation level adaptation. Link utilization is improved for the entire range of average SINR values, but improvement is more evident for mild interference conditions (SINR $\geq$ 14 dB). Efficient link utilization and reduced blocking ratio lead to significant capacity gains.

We also investigate the dynamic situation with user arrivals and departures. We consider equal user requests that arrive in independent Poisson streams. Each request has an exponentially distributed duration with mean $\tau = 1/\mu = 60$ sec and is active for $\lceil t_d/T_f \rceil$ frames, where t_d is the active period of the request. The measured traffic in Erlangs is $E = \lambda\tau/60$, where rate λ is the number of requests per minute. Figure 3 shows the blocking ratio for such a dynamic scenario under varying traffic load regimes. BCS algorithm leads to low blocking ratios $(1-3\%)$ for light and moderate traffic (i.e. less that 10 Erlangs), whereas blocking ratio is 30% for this traffic range with no user rearrangements. The difference in blocking ratio between BCS and other policies increases for higher traffic loads. LLC algorithm has satisfactory performance only for light traffic. The dominance of BCS algorithm in blocking ratio and link utilization is viewed as throughput enhancement. In a dynamic environment, the system can respond better to traffic increase or link deterioration and maintain a high throughput.

VI. Conclusion

In this paper we considered the problem of intra-cell carrier allocation. The determination of an assignment of users to carriers so that the minimum number of carriers (or number of timeslots) is used, is a hard optimization problem. In section IV we identified the intractability of the problem for non-splittable user requirements and provided an optimal solution for splittable user requirements, assuming that a feasible allocation of channels in a carrier is given. If this assumption is eliminated, the latter problem becomes intractable. Therefore some heuristic algorithms along the lines of the simplified method must be applied, so that result will be close to the optimal one. Such a heuristic algorithm (BCS) is proposed in section III. The BCS algorithm provides an efficient solution in the sense that each user is assigned to the carrier which results in the least channel occupancy. It also achieves low blocking ratio and high link utilization. The algorithm provides a first insight in the accomplishment of resource allocation with adaptive modulation and can be applied in multi-carrier systems.

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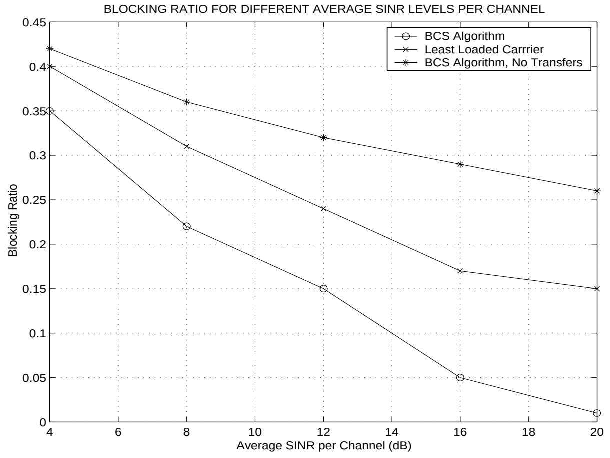

Fig. 1. Blocking ratio as a function of interference conditions for the static case.

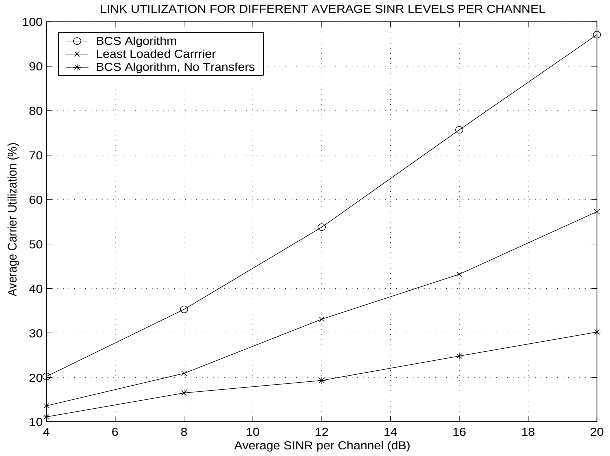

Fig. 2. Link utilization as a function of interference conditions for the static case.

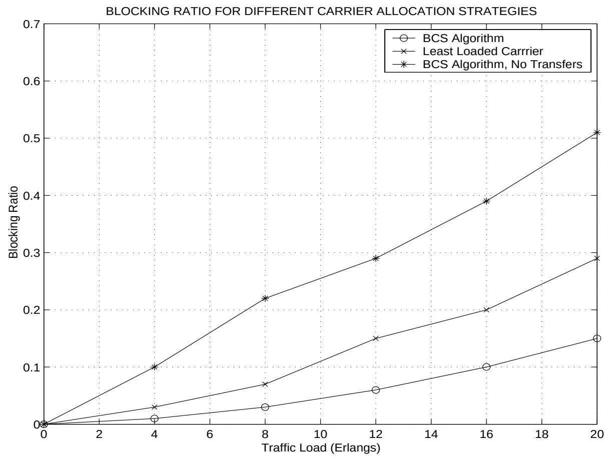

Fig. 3. Blocking ratio as a function of interference conditions in a dynamic environment.