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Adaptive Downlink Resource Allocation Strategies for Real-Time Data Services in OFDM Cellular Systems

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This paper presents a detailed performance analysis of adaptive downlink resource allocation based on users' instantaneous channel responses using power minimization (PM) and bandwidth constrained power minimization (BCPM) strategies. This study shows that, in cellular systems, where interference is a dominant factor, the link outage performance of a resource allocation strategy varies significantly depending on the user channel parameters. In particular, both analytical and simulation results indicate that the PM strategy outperforms BCPM in a mild shadowing environment. However, in severe shadowing conditions, this trend is reversed. This assessment holds true for both flat and frequency-selective fading.

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1. INTRODUCTION

The next generation of mobile communications is envisioned to offer a multitude of services that are available and accessible anywhere and anytime. With the introduction of new multirate, multi-QoS services, the future networks should be designed for economic packet data transfers [1]. These services are highly asymmetrical and require high transmission bandwidth on the downlink. However, due to the limitations of the available frequency spectrum, its efficient use is crucial to the success of the next generation wireless networks. Novel access methods coupled with adaptive resource management techniques, specifically for downlink transmission, require more attention in order to improve the spectral efficiency [1].

Orthogonal frequency division multiplexing (OFDM) is potentially suited for supporting high-speed downlink transmission as it can offer high spectral efficiency due to its robust performance over heavily impaired links. OFDM has been demonstrated as an efficient way to mitigate the adverse effects of frequency selective multipath fading by transmitting signals over a number of flat-faded narrow-band channels. The inherent multicarrier nature of OFDM also allows the use of adaptive modulation and power allocation according to the responses of the narrow-band channels, which can significantly enhance the system performance. In order to exploit fully the advantages of OFDM in cellular systems, dynamic allocation techniques need to be devised, which efficiently use the resources such as bandwidth, power and modulation to increase the spectral efficiency of the system.

Resource allocation for multiuser OFDM has been given much attention in the literature. In [2], the authors proposed an optimization criterion to minimize the transmitted power while satisfying the rate requirements of the users in the system. The authors in [3] give an alternative formulation to maximize the rates of the users while satisfying power constraints. A more generalized formulation in terms of maximizing the average utility function of the users is given in [4] and algorithms are proposed in [5]. The above described formulations are pertinent to an orthogonal frequency division multiple access (OFDMA) type system in which frequency division is used as a multiple access mechanism. Alternatively, spread-spectrum (SS) techniques, such as code division multiple access (CDMA), can be used as an access mechanism over OFDM. In this field, several resource allocation algorithms have been proposed that allocate subcarriers and codes to mitigate the effects of frequency-selective fading [6] and Doppler spread for high mobility [7]. Most of the algorithms proposed above can be applied in a single-cell system since interference for other cells is not considered. However, in a multicell environment, the inter-cell interference has a significant impact on the performance of the system. In this scenario, the power minimization approach as proposed in [2] is a logical candidate for resource allocation. The objective of power minimization aims to reduce the transmission (and hence interference) power on all subcarriers, which results in using the lowest possible modulation, and hence a larger transmission bandwidth (i.e., number of subcarriers) to meet the rate constraint. In a distributed cellular system, where the base-stations do not know each other allocations in advance, this allocation strategy leads to using a larger proportion of bandwidth, which increases the probability of experiencing interference in other cells. This in itself may not be bad, since if the power of interference is low compared to the signal power (i.e., the channel response of the interference is much lower than that of the signal), then the users will still be able to decode the data with low BER. However, when the power of interference is high, the user will experience outage with high probability since the interference is present in a large fraction of the bandwidth. In this scenario, it may make sense to limit the transmission bandwidth of the users, such that if the subcarriers are chosen in a random manner, the probability of interference will be lower than in the previous case. This implies that, in order to satisfy the user rate requirements, higher modulation and hence higher transmission power will be used on these subcarriers.

A simple resource allocation scheme for the downlink OFDM cellular system known as the best subcarrier allocation (BSA), presented in [8], aims to minimize the required number of subcarriers for transmission, and then the transmission power. A similar formulation was also given in [9] which is more suitable to point-to-point networks. A more detailed problem formulation and analysis was given in [10] and the BSA algorithm was refined to a more optimal strategy known as bandwidth constrained power minimization (BCPM). It was shown that in a severe shadowing environment, BCPM gives a better outage performance than PM since it keeps the probability of interference to a minimum.

The objective of this paper is to present a more general analysis of the two schemes discussed above, in order to have an insight into how the two schemes perform in different environments. Specifically, under what channel conditions would the one scheme perform better than the other. For this purpose we develop analytical models of link outage for both severe and nonsevere shadowing conditions in flat fading conditions. The impact of using lower power (lower modulation and larger bandwidth) versus lower bandwidth (higher modulation and higher power) is studied as the load per cell is increased for the two cases. It is shown in Section 4 that in less severe shadowing environments, using lower power (basis of PM) performs better than using smaller bandwidth (basis of the BCPM strategy), whereas the opposite is true for severe shadowing. In Section 6, the performance of the PM and BCPM strategies is given for a more realistic deployment scenario that uses multiple antenna beams per sector to isolate the effects of interference, using real-time data models [11]. Both severe and nonsevere shadowing environments are simulated and the same performance trend is observed.

The remainder of the paper is organized as follows. In Section 2, problem formulation is given for the two strategies. Section 3 discusses the analytical model used to evaluate the link outage probability in flat fading environment with different levels of shadowing, while Section 4 gives performance results of the two strategies. Section 5 briefly describes the algorithms that can be used to solve the PM and BCPM optimization problems. Finally, in Section 6, the performance of the two schemes (using the algorithms in Section 5) is evaluated for real-time data services in different shadowing environments.

2. RESOURCE ALLOCATION IN OFDM SYSTEMS

The aim of resource allocation is to deliver the traffic of multiple users within the given system bandwidth while meeting the QoS requirements. The users' traffic translates to a given rate requirement, and the bandwidth of the system is given by the total number of subcarriers used in the cell, each having a fixed symbol rate. The rate constraint can be met using adaptive modulation (also referred to as bit loading) on all subcarriers such that the total rate transmitted on all the subcarrier equals the total rate requirement of the users. The QoS on the other hand is greatly affected by time-varying channel conditions in a wireless cellular environment. In addition, cochannel interference is a major factor that affects the link outage probability. From this perspective, one strategy of resource allocation would be to transmit the lowest amount of power while satisfying the rate constraints, which is the power minimization strategy. The other is to minimize the probability of experiencing interference, which is the basis of using minimum bandwidth (BCPM) required to satisfy user constraints. The mathematical formulation of the two problems is given as follows.

2.1. Power minimization (PM)

The aim of power minimization is to use the least amount of power to deliver all of the users' traffic in the given bandwidth. The optimization problem can be mathematically stated as follows:

$$\min \sum_{n=1}^{N}\sum_{k=1}^{K} p_{n,k} = \sum_{n=1}^{N}\sum_{k=1}^{K} \rho_{n,k}\frac{f_P(c_{n,k})}{\gamma_{n,k}} \tag{1}$$

subject to

$$c_{n,k} \in \{0, c_0, c_1, \ldots, c_\eta\}, \quad \text{where } c_i < c_{i+1}; \tag{2}$$

$$\sum_{k=1}^{K} \rho_{n,k}c_{n,k} \geq b_n \quad \forall n \in \{1, 2, \ldots, N\}; \tag{3}$$

$$\sum_{n=1}^{N} \rho_{n,k} \leq 1 \quad \forall k \in \{1, 2, \ldots, K\}, \qquad \rho_{n,k} = \begin{cases} 0 & \text{if } c_{n,k} = 0, \\ 1 & \text{if } c_{n,k} > 0; \end{cases} \tag{4}$$

where

(i) n is user index,
(ii) N is total number of users,
(iii) k is subcarrier index,

(iv) K is total number of subcarriers,

(v) $p_{n,k} = \rho_{n,k} f_P(c_{n,k})/\gamma_{n,k}$ is power on the kth subcarrier of the nth user with $c_{n,k}$ bits,

(vi) $c_{n,k}$ is the bit loading level corresponding modulation and coding scheme,

(vii) $f_P(\cdot)$ is power function corresponding to the bit loading level $c_{n,k}$,

(viii) $\gamma_{n,k}$ is channel attenuation on the kth subcarrier of the nth user,

(ix) b_n is the number of bits per OFDM symbol required by the nth user.

Constraints (2)–(4) in the above-stated problem formulation aim to satisfy the user rate requirements to achieve the objective of minimum power. In order to meet the required rates in constraint (3) with the smallest power, the selection of bit loading levels, $c_{n,k}$, in constraint (2) tends to use low values c_i and hence, a large amount of subcarriers. As a result, this increases the occurrence of interference in subcarriers.

2.2. *Bandwidth constrained power minimization (BCPM)*

The BCPM strategy aims to use the minimum number of subcarriers to satisfy the rate requirement with minimum power. Alternatively, the problem can be stated as minimizing power while satisfying the user rate requirements with the smallest possible number of subcarriers. Consider the rate requirement of the user n represented by the required number of bits per OFDM symbol, b_n. The smallest possible number of subcarriers, $S_n^{\min}$, to satisfy b_n is obtained by using the highest bit loading level, c_η, that is, $S_n^{\min} = \lceil b_n/c_\eta \rceil$. Therefore, to satisfy the user rate requirements with the smallest possible number of subcarriers we can add another constraint for the new *bandwidth-constrained power minimization* (BCPM), stated as follows:

$$\min \sum_{n=1}^{N}\sum_{k=1}^{K} p_{n,k} = \sum_{n=1}^{N}\sum_{k=1}^{K} \frac{\rho_{n,k} f_P(c_{n,k})}{\gamma_{n,k}} \quad (5)$$

subject to

$$c_{n,k} \in \{0, c_0, c_1, \dots, c_\eta\}, \quad \text{where } c_j < c_{j+1}; \quad (6)$$

$$\sum_{k=1}^{K} \rho_{n,k} c_{n,k} \geq b_n \quad \forall n \in \{1, 2, \dots, N\}; \quad (7)$$

$$\sum_{n=1}^{N} \rho_{n,k} \leq 1 \quad \forall k \in \{1, 2, \dots, K\};$$

$$\rho_{n,k} = \begin{cases} 0 & \text{if } c_{n,k} = 0, \\ 1 & \text{if } c_{n,k} > 0; \end{cases} \quad (8)$$

$$\sum_{k=1}^{K} \rho_{n,k} \leq S_n^{\min} = \left\lceil \frac{b_n}{c_\eta} \right\rceil \quad \forall n \in \{1, 2, \dots, N\}. \quad (9)$$

It is noted that constraint (9) in the BCPM problem may increase the minimum power as compared to that in the PM problem.

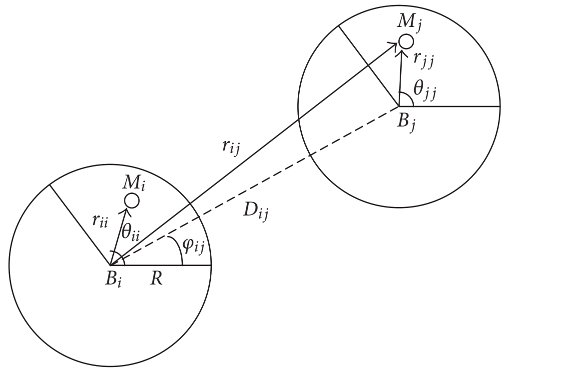


Figure 1: Interaction of two cells.

3. EFFECTS OF INTERFERENCE IN FLAT FADING ENVIRONMENT

For PM strategy, the goal would be to minimize the modulation on each subcarrier and, as a consequence, the number of subcarriers is increased to support the rate requirement. Whereas for BCPM strategy, the aim would be to transmit in the least number of subcarriers by increasing modulation level in each subcarrier. In order to understand the impacts of the two strategies on the system performance, we develop an analytical framework to evaluate the performance of the users in terms of expected link outages as a function of the system load in terms of the number of users, and the number of subcarriers used to deliver the rate requirement. The framework of outage probability calculation involves accounting for flat fading and shadowing with cochannel interference. Given the number of users in the system, the number of subcarriers allocated per user and the signal-to-interference ratio (SIR) required for the modulation/coding scheme in use, the analysis gives the expected outage probability. In this section, we show that the relative performance of PM and BCPM strategies highly depends on the level of shadowing. Section 3.1, gives an overview of the system and the probability density functions (pdf) that are required to derive the expected outage for a given number of users. These results will be used in Section 3.2 where the overall expected outage probability is derived.

3.1. *System model*

We consider a cellular system with 3 sectors/cell, assuming that the path-loss model has the following general form:

$$\mathrm{PL}_{ij} = r_{ij}^{-\beta}, \quad (10)$$

where i is the index of the ith base-station and j is the index of the jth user, and r_{ij} is jth user's distance from the ith base station. Let D_{ik} be the distance and ϕ_{ik} be the angle between base-station i and base-station k, and R be the cell radius. These relations are shown in Figure 1. Note that the subscript ii represents the case where both the base-station and the user are of the same cell. Hence, PL_{jj} is the pathloss, r_{jj} is the distance of user j from its cell's base-station, and θ_{jj} is the angle of the user with respect to his base-station (as indicated in Figure 1).

The distance from the ith base-station to the user j can be expressed in terms of D_{ij}, ϕ_{ij}, r_{jj} and θ_{jj} as follows:

$$r_{ij}^2 = r_{jj}^2 + D_{ij}^2 - 2r_{jj}D_{ij}\cos\left(\phi_{ij} + \pi - \theta_{jj}\right). \tag{11}$$

In presence of Rayleigh fading and log-normal shadowing, the pdf of instantaneous received power ps_{ij} from the ith base-station to the jth user can be given as [12] the following equation assuming the transmission power of base-station i is 0 dB:

$$f_{ps_{ij}}(ps_{ij}) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{\infty}\exp\left(-pl_{ij}\right)\exp\left\{-ps_{ij}\exp\left(-pl_{ij}\right)\right\} \times \exp\left\{-\frac{\left(pl_{ij} - m_{ij}\right)^2}{2\sigma^2}\right\}\partial pl_{ij}, \tag{12}$$

where pl_{ij} is the logarithmic local mean power with logarithmic area mean power m_{ij} and logarithmic standard deviation σ expressed in natural units. The logarithmic area mean power is given as $m_{ij} = -\beta\ln(r_{ij})$ and the σ is related to decibel standard deviation σ_{dB} as $e^{\sigma} = 10^{\sigma_{\text{dB}}/10}$.

In the PM and BCPM strategies, the power control is performed on the instantaneous channel response, which has both the fading and shadowing components (as described above). The first step is to derive the pdf of the received power of one interferer, given that the signal power is normalized at 1 (0 dB). Appendix A presents the derivation [10] for shadowing standard deviation larger than 10 dB, by approximating the received interference as a log-normal distributed component [12]. Unfortunately, the results become inaccurate for lower shadowing standard deviation. For less severe shadowing, an alternative method based on Padé approximation [13] to derive the pdf of the received interference power from one user is given in Appendix B. Our derivation shows that the approximated distribution has a form of a mixture of Pareto distributions. Finally, we give the distribution of users within a cell. If the users are uniformly distributed in the sector then the pdf of r_{ii} and θ_{ii} for all i can be given by

$$f_{r_{ii}}(r_{ii}) = \begin{cases} \dfrac{2r_{ii}}{R^2} & 0 < r_{ii} \le R, \\ 0 & \text{elsewhere}, \end{cases}$$
$$f_{\theta_{ii}}(\theta_{ii}) = \begin{cases} \dfrac{3}{2\pi} & 0 < \theta_{ii} \le \dfrac{2\pi}{3}, \\ 0 & \text{elsewhere}. \end{cases} \tag{13}$$

3.2. Expected outage probability

Outage occurs when the desired signal does not meet the required SIR for reliable communications. The interference arises from the closest users that use the same subcarrier. Let $j = 0$ be the user of interest. Given n interfering users using the same subcarrier as the user 0, the SIR can be given as

$$(\text{SIR} \mid n) = \frac{pt_{00}\cdot ps_{00}}{pc_{n0}} = \frac{1}{pc_{n0}}, \quad \text{where } pc_{n0} = \ln\left(\sum_{i=1}^{n} e^{pc_{i0}}\right). \tag{14}$$

The probability of outage given n interfering users can be expressed as

$$\Pr(\text{outage} \mid n) = \Pr(\text{SIR} < z) = \Pr\left(pc_{n0} > \frac{1}{z}\right) = \int_{1/z}^{\infty} f_{pc_{n0}}(pc_{n0})\,\partial pc_{n0}, \tag{15}$$

where z is the minimum SIR protection ratio required for reliable communications. Note that z is different for different modulation/coding schemes used in the system.

For severe shadowing conditions, where the individual interference components are approximated by log-normal distributions, the pdf of pc_{n0} can be approximated by another log-normal distribution, that is,

$$f_{pc_{n0}}(pc_{n0}) = \frac{1}{\sqrt{2\pi}\hat{\sigma}_{cn}pc_{n0}}\exp\left\{-\frac{\left(\ln pc_{n0} - \hat{m}c_{n0}\right)^2}{2\hat{\sigma}_{cn}^2}\right\}, \tag{16}$$

where the mean $\hat{m}c_{n0}$ and standard deviation $\hat{\sigma}_{cn}$ can be derived by using the method proposed by Schwarz and Yeh [14]. Hence the outage probability given users n can be stated as follows:

$$\Pr(\text{outage} \mid n) = \int_{1/z}^{\infty}\frac{1}{\sqrt{2\pi}\hat{\sigma}_{cn}pc_{n0}}\exp\left\{-\frac{\left(pc_{n0} - \hat{m}c_{n0}\right)^2}{2\hat{\sigma}_{cn}^2}\right\}\partial\hat{p}c_{n0}. \tag{17}$$

For less severe shadowing conditions, the interference is a mixture of Pareto-distributed components, and a closed-form pdf of the sum in (14) is difficult to find analytically by using the Padé approximation. An alternative approach is to approximate the sum of independent Pareto random variables by the pdf of the largest one, since it is the dominant term in the sum. The cdf of the maximum of the distributions is readily given as follows:

$$F_{p_{c_{n0}}}(p_{c_{n0}}) \simeq F(p_{\max}) = \prod_{i=1}^{n}F_{p_{c_{i0}}}(p_{c_{i0}}) = \prod_{i=1}^{n}\left\{\sum_{l=0}^{M}\sum_{m=0}^{M}\lambda_{ms}\lambda_{lt}\left(1 - \left[\frac{q_{ms}}{q_{lt}}pc_{i0} + 1\right]^{-1}\right)\right\}. \tag{18}$$

The outage probability for the n interferers can then be given simply by using the following expression:

$$\Pr(\text{outage} \mid n) = 1 - F_{pc_{n0}}\left(\frac{1}{z}\right). \tag{19}$$

Table 1: Modulation/coding schemes and parameters.

Modulation and coding schemes	Bandwidth efficiency	N_{scu} for 20 kbps	N_{scu} for 120 kbps	z_{dB} required at BER = 10^{-6}
rate-1/2 QPSK	1 bps/Hz	2	12	2 dB
rate-1/2 16QAM	2 bps/Hz	1	6	7.01 dB
rate-3/4 16QAM	3 bps/Hz	—	4	11.17 dB

The expressions of outage above are valid for a given set of mean powers of transmit and receive power of interfering users, which in turn depend on the distance of user i and user 0 from their corresponding base stations. Hence, this expression is conditioned on the distance vector $R = \{r_{00}, r_{11}, \ldots, r_{nn}\}$ and θ_{oo}. In order to get the average outage probability, we generate M samples of the vector R chosen from $f_{r_{ii}}(r_{ii})$ and θ_{oo} chosen from $f_{\theta_{oo}}(\theta_{oo})$, and average the result.

The next step is to derive the user outage probability in terms of system load (represented by the number of users N in each sector) and the number of subcarriers N_{scu} allocated per user. Define the load per subcarrier per sector, $L_s = NN_{\text{scu}}/K$, where K is the number of subcarriers per sector, and T as the total number of interfering sectors, with $I = \{I_t, 1 \le t \le T\}$ as the set of indexes of the interfering sectors. Let the system states S_j, $0 \le j \le 2^T - 1$, represent all possible combinations of the elements of I, which are currently interfering with user 0, for example, $S_0 = \{\emptyset\}$, $S_1 = \{I_1\}$, $S_2 = \{I_2\}, \ldots, S_{T+1} = \{I_1, I_2\}$, $S_{2^T-1} = \{I_1, I_2, \ldots, I_T\}$. Assume that the bandwidth is divided into K/N_{scu} contiguous sets of N_{scu} subcarriers each. For uniform distribution in allocating subcarrier set, the probability of being in state $S_{j,k}$ is

$$\Pr\{S_j\} = (L_s)^{n_j}(1 - L_s)^{T-n_j}, \tag{20}$$

where n_j is the number of interferers in the state S_j. It follows that $\Pr\{\text{outage} \mid S_j\} = \Pr(\text{outage} \mid n_j)$ given in (17) and (19) and the total probability of outage is

$$\Pr\{\text{outage}\} = \sum_{j=0}^{2^T-1} \Pr\{\text{outage} \mid S_j\} \Pr\{S_j\}. \tag{21}$$

The above derivation gives the analytical framework for the performance evaluation of the PM and BCPM criterions. Power minimization alone tends to increase the number of subcarriers in order to reduce the required modulation level and hence the transmitted power; whereas bandwidth minimization in order to reduce the probability of interference tends to reduce the number of subcarriers used and increase the modulation levels and the corresponding power.

4. PERFORMANCE IN FLAT FADING AND SHADOWING ENVIRONMENT

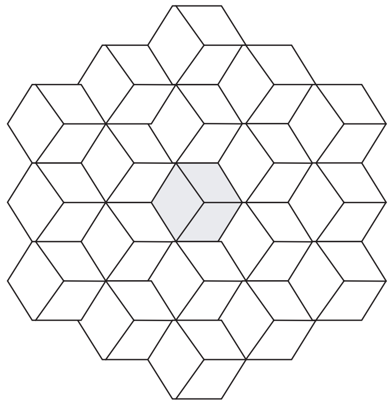
Consider an OFDM system with 180 subcarriers (60 subcarriers per cell). Each subcarrier has a bandwidth of 10 kHz and can ideally support 10ksps. We investigate the performance of the PM and BCPM strategies for the two following traffic scenarios. In the first scenario, each user requires 20 kbps (low-rate scenario). In this case, for each user, we can use 2 rate-1/2 QPSK subcarriers with a required SIR of 2 dB or 1 rate-1/2 16-QAM subcarrier with a required SIR of 7.01 dB. In the second scenario, each user needs 120 kbps (high-rate scenario). This can be supported by 12 rate-1/2 QPSK, 6 rate-1/2 16-QAM, or 4 rate-3/4 16-QAM subcarriers with increased SIR requirements. Table 1 summarizes the modulation and coding techniques taken from [15] with the corresponding rate and SIR protection ratio for reliable communication (BER = 10^{-6}), and also gives the number of subcarriers required by each modulation for the low- and- high rate scenarios. The analysis is carried out for $\sigma_{\text{dB}} = 5$ dB and 10 dB.

The analysis is also verified by simulations with a 3-sector, 19-cell system shown in Figure 2(a) in the presence of Rayleigh flat fading and path-loss exponent $\beta = 3.5$. Within one cell, each sector has a hard division amongst the subcarriers to allocate so that they do not interfere with each other. For analytical results, only 2 first-tier cells and 5 second-tier cells shown in Figure 2(b) are taken into account since they contain the dominant interferers.

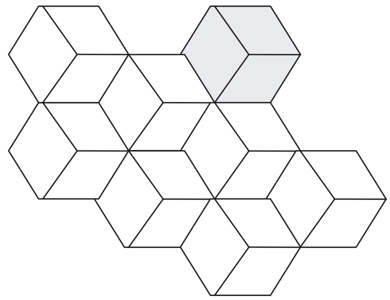
Figures 3(a) and 3(b) show the results for low-rate (20 kbps) and high-rate (120 kbps) scenarios, respectively. Solid lines indicate the analytical results for severe shadowing with $\sigma_{\text{dB}} = 10$ dB, while dashed-dotted lines represents the mild shadowing with $\sigma_{\text{dB}} = 5$ dB.

For both low- and high-rate data scenarios, in the case of mild shadowing with standard deviation of 5 dB, the PM approach using low bandwidth-efficient modulation/coding schemes (e.g., rate-1/2 QPSK) provides better performance (i.e., lower outage probability) than the BCPM approach. However, for severe shadowing, the trend is reversed. This can be explained by the fact that, for the same margin separating the mean signal and interference powers, the chance of crossing the protection ratio (i.e., margin) in mild shadowing scenarios is smaller than that in the case with severe shadowing (i.e., large shadowing variance). Hence, minimizing power alone in the severe shadowing case is not enough to guarantee low link outage. Instead, reducing the probability of interference by using minimum bandwidth yields a higher protection against outage. On the other hand, in a low shadowing scenario, as the minimum power approach already gave sufficient protection against outage, using BCPM approach may increase the interfering power level that leads to higher outage.

Figure 3(b) shows that, in the higher-rate case (120 kbps), for mild shadowing with $\sigma_{\text{dB}} = 5$ dB, going from 12 to 6 subcarriers does not have as drastic an impact on performance as from 6 to 4 subcarriers. This implies that there is a limit on the SIR threshold, which would severely

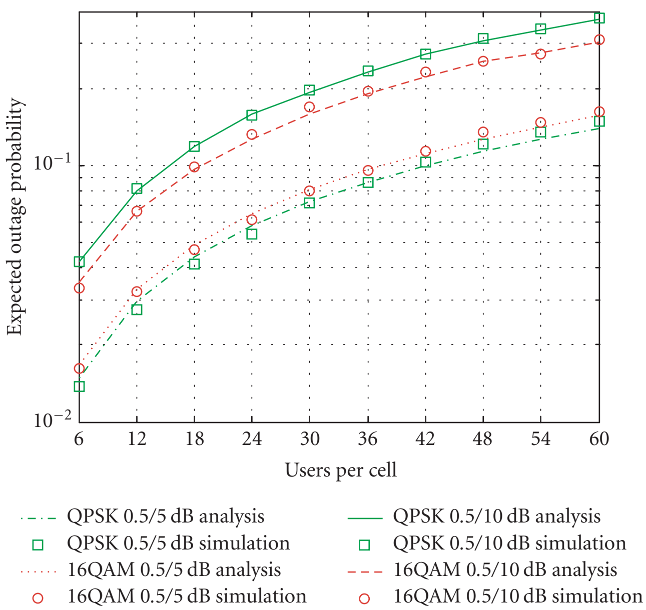


(a) Simulation system with 19 cells, 2-tier interferers.

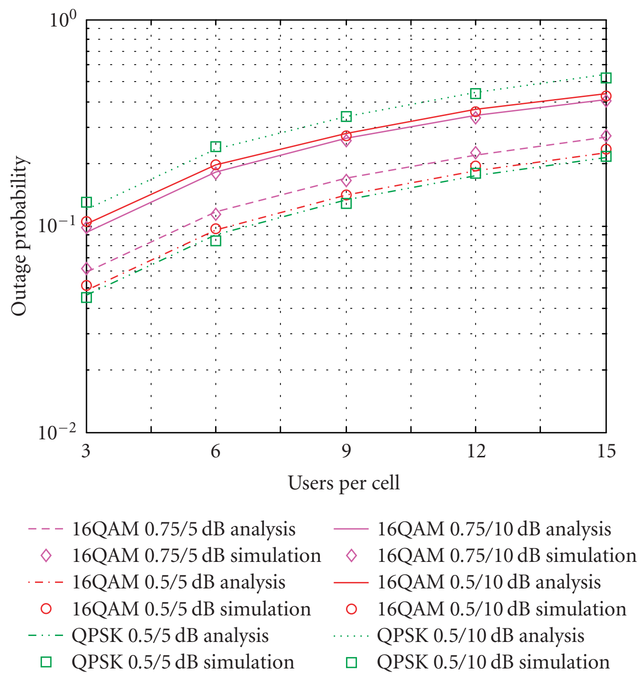


(b) Analytical model with 2 first-tier and 5 second-tier interferers.

Figure 2: Cellular system: simulation and analytical models.



(a) Outage probability for 20 kbps.



(b) Outage probability for 120 kbps.

Figure 3: Performance comparison of various modulation/coding schemes.

degrade the performance if crossed. The results support the power minimization argument that keeping lower modulation (with lower SIR thresholds) would yield better performance for mild shadowing cases. The reverse situation for the case of severe shadowing with $\sigma_{\text{dB}} = 10\,\text{dB}$ is also shown in Figure 3(b): moving from 4 to 6 subcarriers has smaller performance penalty than from 6 to 12 subcarriers. This is consistent with the argument that the probability of interference is the dominant factor indicating the system performance in severe shadowing.

The advantage of the analytic model presented in this paper is that it can give insight into the performance of resource allocation algorithms without performing extensive simulations. In fact, as will be seen in Section 6 for performance of PM and BCPM strategies in frequency selective fading, the same performance trend with respect to shadowing is observed. However, for frequency selective channel models and user traffic models, simulation is necessary for exact performance evaluation in terms of outage, throughput, and/or delay.

5. ALGORITHMS FOR RESOURCE ALLOCATION

In this section, we discuss algorithms for the two strategies that we implement for the performance evaluation of real-time data services.

5.1. Power minimization

There have been several proposed algorithms in the literature that try to solve the power minimization problem. In [2], Lagrangian relaxation technique is used to derive an iterative technique of allocation. This approach has high complexity in the number of iterations required to solve the problem. The brute-force integer programing formulation and its linear programing counterpart have been discussed in [16]. This approach has even higher complexity, although it performs better than the previous approach. In [17], an intuitive approach to power minimization was proposed that divides the allocation problem into three steps: (i) bandwidth allocation, (ii) subcarrier assignment, and (iii) bit loading. This is the approach we use in implementing the power minimization algorithm. The subcarrier assignment proposed in [17] is replaced by the one in [18] since this algorithm gave better performance in terms of minimum power. The bit loading algorithm is the greedy approach proposed in [19], which is optimal for single user allocation. The details of the algorithms can be found in respective literature. Here, we summarize them as follows.

(i) Bandwidth allocation.

(1) Initialize the subcarrier allocation for user n to $S_n = S_n^{\min} = \lceil b_n/c_\eta \rceil$, where S_n is the number of subcarriers assigned to the user n.

(2) While $\sum_{n=0}^{N} S_n < N$,

(a) let $\partial r_n = ((S_n+1)/\bar{\gamma}_n) f_p(b_n/(S_n+1)) - (S_n/\bar{\gamma}_n) f_p(b_n/S_n)$ for all n, where $\bar{\gamma}_n$ is the average channel response of user n and ∂r_n is the power reduction if one more subcarrier was allocated to the user;

(b) assign the additional subcarrier to the user who causes the minimum power reduction, that is,

- $m = \arg\min_n \partial r_n$,
- $S_m = S_m + 1$.

(ii) Subcarrier assignment.

(1) Initialize each user n by sorting his subcarriers in ascending order in terms of $f_n/\gamma_{n,k}$, where $f_n = f_P(c_n)$ and $c_n = \lceil b_n/S_n \rceil$. Here c_n is seen as the average number of bits loaded per subcarrier. The actual number of bits per subcarrier is only decided in the bit loading stage, and c_n is used here conveniently to simplify the subcarrier assignment process.

(2) Allocate in a round-robin manner the best unused subcarrier to user n from the above list of sorted subcarriers until its subcarrier requirement is satisfied.

(3) Determine the effective power reduction $\Delta p_{ij} = \partial p_{ij} + \partial p_{ji}$ for each user pair (i, j), where

(a) ∂p_{ij} is the minimum power reduction among all subcarriers of i when a subcarrier of i is reassigned to j, that is, $\partial p_{ij} = \min_k\{\partial p_{ij}^k\}$, and $k_{ij} = \arg\min_k\{\partial p_{ij}^k\}$ and $\partial p_{ij}^k = f_j/\gamma_{j,k} - f_i/\gamma_{i,k}$ is the potential power reduction when subcarrier k belonging to user i is reassigned to user j.

(4) Determine $\Delta p_{\min} = \min\{\Delta p_{ij}\}$ amongst all user pairs (i, j). If $\Delta p_{\min} < 0$, perform the corresponding subcarrier re-assignment; otherwise stop, the power cannot be reduced further.

(iii) Bit loading.

(1) Initialize for each user n the bit loading level on each subcarrier k assigned to user n in the previous step to be $c_{n,k} = 0$. Let the initial power increment be $\partial p_{n,k} = f_p(1)/\gamma_{n,k}$ on each subcarrier.

(2) For each user n, while $\sum_{k=1}^{K} c_{n,k} < b_n$,

(a) $l = \arg\min_k \partial p_{n,k}$,
(b) $c_{n,k} = c_{n,k} + 1$,
(c) $\partial p_{n,k} = f_p(c_{n,k}+1)/(\gamma_{n,k}) - f_p(c_{n,k})/(\gamma_{n,k})$.

5.2. Bandwidth constrained power minimization

For this strategy of resource allocation, a simple algorithm that assigned the minimum number of best available subcarriers to the users was proposed in [8]. In [10], a more optimal approach was proposed that follows the three-step approach described above. However the first two steps are replaced by the following.

(i) Bandwidth allocation.

(1) For each user n, allocate the minimum number of subcarriers that would satisfy the users rate requirement, determined as $S_n = S_n^{\min} = \lceil b_n/c_\eta \rceil$.

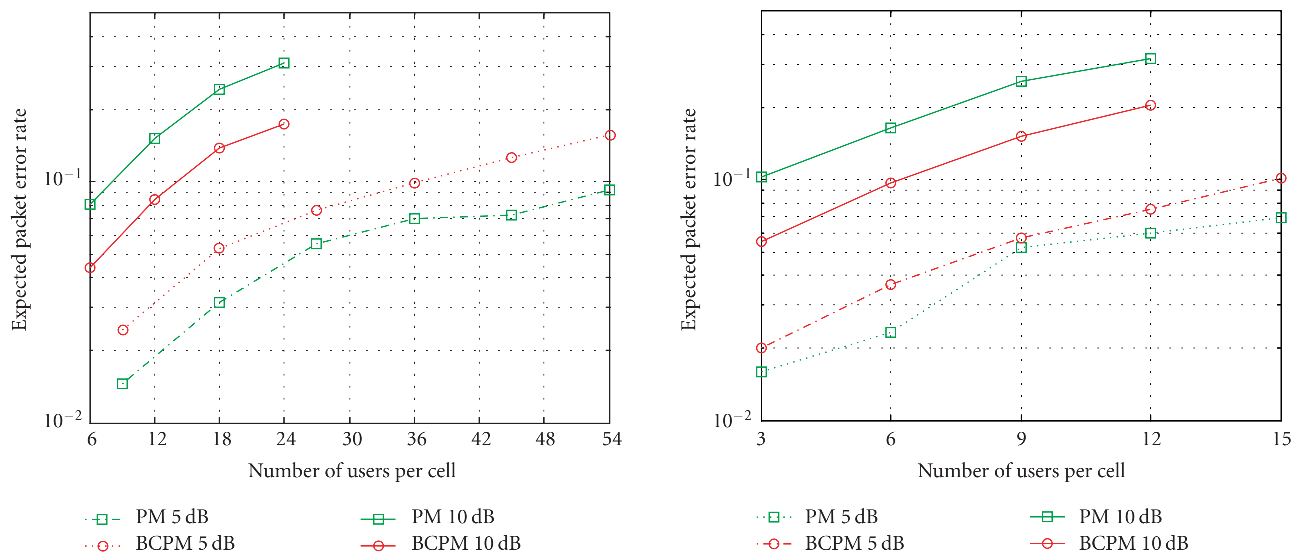
(ii) Subcarrier assignment.

(1) For each user n, sort the subcarriers in ascending order in terms of $f_n/\gamma_{n,k}$.

(2) Allocate in a round-robin manner the best unused subcarrier to user n from the above list of sorted subcarriers until its subcarrier requirement is satisfied.

(3) Determine the effective power reduction $\Delta p_{ij} = \min\{\partial p_{ij} + \partial p_{ji}, \partial p_{ij} + \partial p_{ji} + \partial p_{ii}, \partial p_{ij} + \partial p_{ij} + \partial p_{jj}\}$ for each user pair (i, j), where

(a) ∂p_{ij} is the minimum power reduction amongst all subcarriers of i when a subcarrier of i is reassigned to j, that is, $\partial p_{ij} = \min_k\{\partial p_{ij}^k\}$, and $k_{ij} = \arg\min_k\{\partial p_{ij}^k\}$ and $\partial p_{ij}^k = f_j/\gamma_{j,k} - f_i/\gamma_{i,k}$ is the potential power reduction when subcarrier k belonging to user i is reassigned to user j;



(a) 32 kbps.

(b) 64 kbps.

FIGURE 4: Performance of PM and BCPM schemes in supporting real-time data services.

(b) ∂p_{ii} is the minimum power reduction amongst the unused subcarriers when an unused subcarrier k' is used instead of k_{ji}, where k_{ji} was reassigned from user j to user i, that is, $\partial p_{ii} = \min_{k'}\{f_i/\gamma_{i,k'} - f_i/\gamma_{i,k_{ji}}$ for all k' of ununsed subcarriers $\}$. Determine $\Delta p_{\min} = \min\{\Delta p_{ij}\}$ among all user pairs (i, j). If $\Delta p_{\min} < 0$, perform the corresponding subcarrier reassignment; otherwise stop, the power cannot be reduced further.

(iii) Bit loading.

(1) Initialize for each user n the bit loading level on each subcarrier k assigned to user n in the previous step to be $c_{n,k} = 0$. Let the initial power increment be $\partial p_{n,k} = f_p(1)/\gamma_{n,k}$ on each subcarrier.

(2) For each user n, while $\sum_{k=1}^{K} c_{n,k} < b_n$,

(a) $l = \arg\min_k \partial p_{n,k}$,
(b) $c_{n,k} = c_{n,k} + 1$,
(c) $\partial p_{n,k} = f_p(c_{n,k} + 1)/\gamma_{n,k} - f_p(c_{n,k})/\gamma_{n,k}$.

Note that this is the same bit-loading algorithm used for power minimization.

6. PERFORMANCE OF REAL-TIME DATA SERVICES IN FREQUENCY SELECTIVE FADING AND DIFFERENT SHADOWING ENVIRONMENTS

For performance evaluation of data services, we simulate a cellular environment with a 19-cell configuration that includes the effects of up to second-tier interferers. Each hexagonal cell is divided into three sectors, with 3 beams per sector. The OFDM system has 90 traffic subcarriers (30 subcarriers per sector); each having a bandwidth of 10 kHz and can support a symbol rate of 10 ksps (same assumption as in Section 3). The modulation and coding levels are the same as used in Section 3, which give a spectral efficiency of 1–4 bps/Hz. The resource allocation interval is 20 ms in which the channel is assumed to be unchanged. The modified Hata model is used to represent the path-loss model with a path-loss exponent of 3.5.

Shadowing is assumed to be correlated log-normal using the method stated in [20] with standard deviation of 5 and 10 dB and correlation distance of 20 m, which is commonly used for a vehicular environment. The simulated multipath power delay profiles are vehicular-B [11], and Rayleigh fading is assumed with the Jake's method [20]. At the beginning of the simulation, the mobiles are dropped in the sectors with speed of 30 km/h. No handoffs are simulated, and it is assumed that if the mobile leaves the sector from one edge, it enters from another to preserve the number of mobiles in the area during simulation.

We simulate two data rate scenarios. The low-rate scenario consists of a constant rate of 32 kbps [11] with packet sizes of 320 bits at a constant inter-arrival time of 10 ms. The high-rate scenario consists of a constant rate of 64 kbps [11] with packet sizes of 640 bits at a constant inter-arrival time of 10 ms. The packet error rate is used as a performance measure that captures the link outage.

Figure 4(a) shows the performance results for 32 kbps in both 5 and 10 dB shadowing scenarios. It can be seen that the same trend is followed in this figure as the analysis. In a mild shadowing environment ($\sigma_{\text{dB}} = 5$ dB), the PM scheme performs better with 1.5 times more users at PER = 10%. On the other hand, in a severe shadowing environment ($\sigma_{\text{dB}} = 10$ dB), the BCPM gives twice as many users as PM at PER = 10%.

Figure 4(b) also gives similar conclusions as the analysis for 64 kbps data services: PM outperforms BCPM for mild shadowing ($\sigma_{\text{dB}} = 5$ dB) and the situation is reversed for severe shadowing ($\sigma_{\text{dB}} = 10$ dB). However, the difference in performance between PM and BCPM is smaller. This may be attributed to the fact that at high rates, a lot more subcarriers are employed for the lower bandwidth-efficient modulation scheme (e.g., at 15 users per cell, rate-1/2 QPSK would need 105 subcarriers). However, since there are only a limited number of subcarriers, the PM algorithm would have to use higher bandwidth-efficient modulation schemes in some subcarriers to satisfy the rate requirements. Hence, the difference in performance between PM and BCPM at higher rates and higher loads is less pronounced.

7. CONCLUSIONS

In this paper, we have shown that in downlink OFDM mobile cellular systems, the probability of interference occurrence is an important factor in determining the system performance, which should be accounted for in the resource allocation strategy. The proposed BCPM schemes to minimize first the number of subcarriers and then power minimization in satisfying user rate requirements can significantly enhance link performance. We derived a framework to analyze the expected outage probability of different transmission bandwidths and corresponding modulation schemes in flat fading and shadowing cellular environment and showed the benefits of constraining number of allocated subcarriers. It was shown that in frequency-selective fading, the BCPM schemes significantly outperform PM strategy alone for both voice and data services.

APPENDICES

A. PDF OF RECEIVED INTERFERENCE POWER FOR SEVERE SHADOWING

The density function of ps_{ij} can be approximated by a log-normal distribution [12] with a reduced logarithmic area mean power $\hat{m}_{ij}$ and an increased logarithmic standard deviation $\hat{\sigma}$ given as follows:

$$\begin{aligned}\hat{\sigma}^2 &= \sigma^2 + \ln(2),\\ \hat{m}_{ij} &= m_{ij} - \frac{1}{2}\ln(2) = -\beta\ln\left(r_{ij}\right) - \frac{1}{2}\ln(2).\end{aligned} \tag{A.1}$$

Hence the approximated pdf of ps_{ij} can be given as

$$f_{ps_{ij}}\left(ps_{ij}\right) = \frac{1}{\sqrt{2\pi}\hat{\sigma}ps_{ij}}\exp\left\{-\frac{\left(\ln ps_{ij} - \hat{m}_{ij}\right)^2}{2\hat{\sigma}^2}\right\}. \tag{A.2}$$

Given the received power pdf based on a transmit power of 1, for a power controlled system, the instantaneous transmit power of user i from base-station i can be given by $pt_{ii} = 1/ps_{ii}$ assuming that the received power of user i is normalized to 1. The corresponding pdf of pt_{ii} is

$$f_{pt_{ii}}\left(pt_{ii}\right) = \frac{1}{\sqrt{2\pi}\hat{\sigma}pt_{ii}}\exp\left\{-\frac{\left(\ln pt_{ii} + \hat{m}_{ii}\right)^2}{2\hat{\sigma}^2}\right\}. \tag{A.3}$$

The interference power from user i's base-station to user j can be given as $pc_{ij} = pt_{ii}\cdot ps_{ij}$, and the corresponding pdf is

$$f_{pc_{ij}}\left(pc_{ij}\right) = \frac{1}{\sqrt{2\pi}\hat{\sigma}_c pc_{ij}}\exp\left\{-\frac{\left(\ln pc_{ij} - \hat{m}c_{ij}\right)^2}{2\hat{\sigma}_c^2}\right\}, \tag{A.4}$$

where

$$\begin{aligned}\hat{m}c_{ij} &= -\hat{m}_{ii} + \hat{m}_{ij}\\ &= \beta\ln\left(r_{ii}\right) + \frac{1}{2}\ln(2) - \beta\ln\left(r_{ij}\right) - \frac{1}{2}\ln(2)\\ &= \beta\ln\left(\frac{r_{ii}}{r_{ij}}\right)\\ &= \beta\ln\left(\frac{r_{ii}}{\sqrt{r_{jj}^2 + D_{ij}^2 - 2r_{jj}D_{ij}\cos\left(\phi_{ij} + \pi - \theta_{jj}\right)}}\right)\end{aligned} \tag{A.5}$$

and $\hat{\sigma}_c^2 = 2\sigma^2 + 2\ln(2)$.

B. PDF OF RECEIVED INTERFERENCE POWER FOR MILD SHADOWING

Padé approximation technique [13] can be used to approximate the pdf of pc_{ij} for mild shadowing case. The power series of a pdf around two points can be expressed as

$$\begin{aligned}h(u) &= \sum_{n=0}^{\infty} c_n u^n, \quad u \longrightarrow 0,\\ h(u) &= \sum_{n=0}^{\infty} d_n u^{-(n+1)}, \quad u \longrightarrow \infty,\\ c_n &= \frac{\mu_n}{n!}(-1)^n, \quad \mu_n = n\text{th moment of pdf},\end{aligned} \tag{B.1}$$

where

$$d_n = f^{(n)}(0), \quad f^{(n)} = n\text{th derivative of pdf} \tag{B.2}$$

Details of the above equations are given in [13]. In the case of received power ps_{ij} given 0 dB transmit power, μ_n and $f^n(0)$ can be derived as

$$\begin{aligned}\mu_n &= n!\exp\left\{nm_{ij} + \frac{1}{2}(n\sigma)^2\right\},\\ f^n(0) &= (-1)^n\exp\left\{-(n+1)m_{ij} + \frac{1}{2}\left[(n+1)\sigma\right]^2\right\}.\end{aligned} \tag{B.3}$$

The Padé approximation is a rational function approximation of the power series and can be used to approximate only the first few terms of $h(u)$. It has the following form:

$$\begin{aligned}P_{(J,K)}^{[M-1/M]}(u) &= \frac{\sum_{n=0}^{M-1} a_n u^n}{1 + \sum_{n=1}^{M} b_n u^n}\\ &= \begin{cases}\displaystyle\sum_{n=0}^{J-1} c_n u^n, & u \longrightarrow 0,\\ \displaystyle\sum_{n=0}^{K-1} d_n u^{-(n+1)}, & u \longrightarrow \infty.\end{cases}\end{aligned} \tag{B.4}$$

Once the coefficients a_n and b_n are found, then a partial fraction decomposition can be done:

$$P_{(J,K)}^{[L/M]} = \frac{\sum_{n=0}^{M-1} a_n u^n}{1 + \sum_{n=1}^{M} b_n u^n} = \sum_{m=1}^{M} \frac{\lambda_i}{u + q_m}. \quad \text{(B.5)}$$

Inverting this expression, we get a mixture of exponential distributions:

$$f(x) = \sum_{m=1}^{M} \lambda_i \exp(-q_m x). \quad \text{(B.6)}$$

Hence, the pdf of ps_{ij} for 0 dB transmit power can be approximated by the above expression. Following the same argument as in Appendix A, the transmit power of a user within the same cell can be given by $pt_{ii} = 1/ps_{ii}$. The interference power from user i's base-station to user j given as $pc_{ij} = pt_{ii}$. $ps_{ij} = ps_{ij}/ps_{ii}$ can now be calculated by transformation of random variables since both ps_{ij} and ps_{ii} follow the same distribution as (B.6),

$$f_{pc_{ij}}(pc_{ij}) = \sum_{l=0}^{M} \sum_{m=0}^{M} \lambda_{ms}\lambda_{lt} \frac{1}{(q_{ms} pc_{ij} + q_{lt})^2}, \quad \text{(B.7)}$$

where q_{ms}, λ_{ms} are the coefficients of received power of interference, and q_{lt}, λ_{lt} are the coefficients for the derived transmit power of the interference.

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