1 Introduction

The fundamental figure of merit that specifies the ultimate performance of cellular systems is the per-cell capacity efficiency, defined as the maximum number of bits/s per cell that can be transmitted reliably at any given cell. The capacity efficiency of single-cell, non-cooperative, direct sequence code division multiple access (CDMA) systems has been thoroughly analyzed in [1] and [2]. Focusing on the asymptotic area, where both the number of users per cell and the number of users in the system grow to infinity, while $\beta = \frac{N}{C} < \frac{1}{2}$ is referred to as the "full load" area, analytical and deterministic limiting expressions for the capacity efficiency of various multiple-access techniques were derived, using sparse random matrix theory tools.

The underlying basic assumption in the above capacity-efficiency analyses is that all active users are (randomly) decided regardless of their received powers. In slow-fading channels, where the channel fading gains are fixed during the considered duration, the above assumption actually implies that the users adjust their rates (and possibly also their powers) as a function of the channel fading level they experience. Via distributions from the receiver (unfortunately, in practice, both feedback and ideal timing of the users' transmission cannot always be accomplished, and motivated by process considerations) we consider in this extended exactly an alternative approach.

Assuming independent (over users) spatially distributed slow-fading channels, and a single-user-rate model is considered, adhering to Wyner's infinite-limited-cell-array setting [3], [4], where only adjacent-cell interference is present and characterized by a single parameter $\beta = L: 0 < \beta = L < 1$, as in [1], [2]. The discussion is confined to asymptotic analysis. Excluding any form of feedback from the receiving node, i.e., for ACOA/ACK type, it is assumed that all users transmit with equal rates and equal powers regardless of the individual fade level. The receiver makes the intra-cell tests according to their received powers, and decides only if the user can see experienced powers, equal to in the same cell, or higher than or equal to the largest integer for which decoding is successful. The scheme is hence referred to as "independent users decoding". In this setup, the receiver at the cell can no longer guarantee reliable decoding of all active users due to the presence of fading (as this channel protocol can be adopted in the setup that simplified users are essentially decoded reliably). The total achievable rate for all available users is referred to as the "single-cell rate capacity", and considered as the figure of merit of future wireless systems. The function of available users (FYG) per cell is assumed to be a system design parameter, and can be controlled and equalized in any way by each user, System performance can be further optimized if the user had also a degree of freedom.

Assuming single-cell-wise processing, four types of multiuser detection strategies are considered. The first is the "conventional" matched-filter detector that uses all channel tap convolution for additive white Gaussian noise (AWGN). The second is the linear MMSE detector that knows the signature (spreading sequences) of all interfering users (both inter-cell and in the same cell), and minimizes the error probability of a linear MMSE filter. The third is a detector that optimally processes the maximum-detectable subset of inter-cell users, while taking into account the structure of the multiuser interference generated by all non-active (inter-cell) users (ignoring their signatures are assumed to be received). Out-of-cell interference is assumed to be AWGN. This detector is referred to herein as the "single-cell optimum (SCO) detector". Finally, as an "equivalent" detector, is considered (analogous to the SCO detector that takes into account the capacity of all underlying multiuser interference (both inter-cell and in-cell), assuming all signatures are known at the receiver, This detector is referred to herein as the "single-cell optimum processing matrix (SCOP) detector". The above four detection strategies are analyzed and compared in terms of the outage cumulative distribution function, analytically derived in function of the fading severity in terms of the outage probability. The model is referred to in [7] and [8] for more details on the derivations.

2 Summary of Results

Examining the outage constrained capacity expressions, and focusing on the low signal-to-noise ratio (SNR) regime, an important property of the strong-user decoding scheme can be observed. Described by $\lambda$, the outage constrained...
capacity, the transmit SNR by $P$, and defining the system average $E_b$ through the relation $P = \frac{1}{2} \ln \frac{E_b}{N_0}$, the minimum received $E_b$ that results in reliable communications is found to be

$$
E_b^{\text{min}} = \frac{Q^{-1}(\alpha - 1)}{1 - Q^{-1}(\alpha - 1)}
$$

where $Q$ denotes the limiting per-cell FER, and $E_b^{\text{min}}$ denotes the inverse function of cumulative distribution function of the fade power levels. Comparing this result to $E_b^{\text{min}} = \ln 2 - 3$ dBm, which corresponds to the case where the two users are quite close [3], the penalty for $E_b^{\text{min}}$ induced by the strongest-user decoding scheme is found to be a factor of $\left(1 - Q^{-1}(\alpha - 1)\right)^{-1}$. This penalty is attributed to the power "wasted" when users fail to be decoded. For the particular case of Rayleigh fading, with minimizing (2-1) with respect to $Q$, it follows that $Q = \ln 2 = 2.7$ dBm, which is achieved for $\alpha = 1 - 1/e$ (being hence the optimum FER in the low SNR regime, for Rayleigh fading channels). As can be observed, a severe penalty of $15.4$ dBm or $3.6$ dB is induced by $E_b^{\text{min}}$ by the strongest-users decoding scheme. In Rayleigh fading channels, a considerable outage capacity is also experienced in both the cases in which the total one-cell interference power equals half of the one-cell interference power. The outage transmission capacity is defined as the (commonly experienced and otherwise randomly observed) range of both the cell load $\alpha$ and the FER. Each optimum parameter is in general functions of $E_b$. For the case of computing the spectral efficiencies of the four detection schemes reproduced from [9] are also included in Fig. 1.

The outage capacity of the maximum-flux distributed monotonically increases with the cell load $\alpha$. It is therefore optimum to take $\alpha = \infty$, and it can be shown that for all $E_b$ values the optimum FER for this detector, in Rayleigh fading channels, is $Q = 1 - 1/e$. The detector is interference limited, as can be seen from Fig. 1, and the outage capacity exactly reaches the limit of $E_b^{\text{min}} = 0.1358$ bits/sec/Hz for $\alpha = 1$ as $\alpha \to \infty$ (as opposed to $E_b^{\text{min}} = 0.1565$ Watts/sec/Hz when all users are decoded).

The SCD detector is also interference limited. The results show that while optimizing with respect to both $\alpha$ and $Q$, it is optimum in terms of the outage constrained capacity to take $\alpha = \infty$, and it can be shown that for all $E_b$ values the optimum FER for this detector, in Rayleigh fading channels, is $Q = 1 - 1/e$. The detector is interference limited, as can be seen from Fig. 1, and the outage capacity exactly reaches the limit of $E_b^{\text{min}} = 0.1358$ bits/sec/Hz for $\alpha = 1$ as $\alpha \to \infty$ (as opposed to $E_b^{\text{min}} = 0.1565$ Watts/sec/Hz when all users are decoded).

For low $E_b$ values, it is optimum to take $\alpha = \infty$, and to compute the outage constrained capacity of the linear MMSE detector, we consider all of the matched filter detectors. However, with the increase of $E_b$, the optimum cell load $\alpha$ starts to decrease beyond a critical $E_b$, which is eventually becoming lower than 1 (note that the detector becomes the signals of users of zero rate). Assuming $E_b \leq \frac{1}{2} E_b^{\text{min}}$, we can then show that

$$
E_b^{\text{opt}} = \frac{2(2 + 4\ln E_b + 1/2)^2}{2 + 4\ln E_b + 1/2} E_b^{\text{min}} \left(1 + 2\ln 2 + 1/2 - 2\ln 2 - 1/2\right)
$$

(2-2)

where $E_b^{\text{opt}}$ is given by (2-1). The linear MMSE detector outperforms the matched filter detector for $E_b > E_b^{\text{opt}}$. The optimum FER decreases with $E_b$, below which $E_b^{\text{opt}} = 1 - 1/e$ for Rayleigh fading channels. For Rayleigh fading and $\alpha = 1$, (2-2) yields $E_b^{\text{opt}} = 1.5$ in $2$ dB. The SCD detector also has the advantage of being interference limited, regardless of the FER. This behavior is in contrast to a single-cell setup (2) with $\alpha = \infty$ and $Q = 1 - 1/e$, which is the optimal capacity of the linear MMSE detector in a single-cell setup, assuming the FER varies with $E_b^{\text{opt}}$ as an appropriate rate, the outage constrained capacity of the detector approaches the optimum spectral efficiency at the high $E_b$ region, as shown in Fig. 2. (Note that a significant performance degradation is still observed in a single-cell setup for the two linear MMSE systems as can be observed from Fig. 1, this is no longer the case.)
when undesirable out-of-cell interference is introduced, and a clear performance degradation is observed as compared to the ultimate spectral efficiency of the detector. Examining the optimum FUU of the detector, it is observed that in the low SNR region where is optimum in size tends to be, the optimum FUU of the SCIQ detector coincides with that of the SCQ detector. However, beyond a critical B which corresponds to the point beyond which the opposite cell load decreases to finite value, the optimum FUU of the SCIQ detector starts to decrease more rapidly with B as compared to that of the SCQ detector, which was in a jump.

To conclude, comparing the outage constrained capacities of all four million detectors for their corresponding optimum spectral efficiencies (SN), the strongest-strength decoding scheme is observed to induce a severe penalty in system performance, emphasizing the crucial role of interference avoidance in the presence of undesirable out-of-cell interference.

References


