Distributed Rate Adaptive Packet Access (DRAPA) for Multicell Wireless Networks

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Abstract

Fueled by the explosive growth of the Internet, applications are demanding higher data rate. As the available radio spectrum is limited in bandwidth, the high capacity can be obtained only through effective use of the available bandwidth. This is one of the major challenges that future generation mobile systems face. The available spectrum has to be spatially reused. The traditional frequency reuse schemes in most celluar networks primarily work on circuit switch basis. However, the traffic of future wireless packet networks is bursty with high peak-bandwidth requirement, which can not be handled efficiently in circuit switched cellular networks. Random access schemes, such as ALOHA are seen as better solutions to bursty packet networks. However, the severe multi-cell co-channel interference may significantly reduce the throughput. A fundamentally different spectrum reuse scheme is required for efficient mobile packet data transmission.

In this paper, we propose a distributed rate adaptive packet access (DRAPA) scheme which inherits the advantages of both the circuit switch based rate adaptation and packet switch based random access. DRAPA allows mobile stations to transmit packets in random access mode independent of the activity of other cells, while pakcet code rate is adjusted according to interference level, so that the retransmisson is controlled at an acceptable level. The DRAPA scheme subsumes two traditional schemes as the extreme cases, and has superior performance over the traditional schemes in terms of throughput and stability.

1 Introduction

In this paper, we consider the MAC design in the presence of multi-cell interference [1, 2, 3]. The present mobile radio systems organize the service area into cells. Each cell is served by one basestation (BS), which represents the interface to the fixed networks. Mobile stations (MS) are assigned to a cell according to their geographical position. Each MS communicates to the BS via a radio channel. Radio channels constitute a finite resource and therefore must be reused in the system based on a pre-determined strategy. A crucial aspect of the frequency reuse is the co-channel interference. The amount of interference that can be tolerated determines the required separation distance between co-channel cells and therefore the efficiency of the network. Fixed frequency reuse with factor $C = 3, 4, 7, \ldots$ is adopted in the traditional cellular systems, e.g., GSM [4]. However, by partitioning the whole bandwidth, the achievable peak rate is reduced by a factor of C. This is particularly inefficient when cells are unevenly loaded. Dynamic channel allocation (DCA) [5, 6, 7] provides a means to share the frequency channels among neighboring cells in a more dynamic and efficient way. However, its implementation is quite involved, even for simple circuit-switched networks.

The traffic of future wireless packet networks is bursty with high peak-bandwidth requirement [8]. It is known that such bursty traffic can not be handled efficiently in circuit switched networks. A fundamentally different spectrum reuse scheme is required for efficient mobile packet data transmission. Studies [1, 9] showed that in high-capacity spectrum-efficient packet-switched network, it is preferably to share the whole spectral resources in all cells, e.g. $C = 1$. However, continuing interference between transmissions from adjacent cells may severely affect the performance of such networks. Although it is possible to avoid collisions of simultaneous transmissions in adjacent cells through basestation coordination, the centralized control complicates the system implementation. Distributed, or at least partial distributed multiple-access schemes are more desirable.

In practice, a packet can be successfully detected if the interference power is sufficiently small. The ability of a receiver detecting a signal in the presence of interference and noise is known as capture effect, and the signal to interference and noise ratio (SINR) threshold needed to allow capture is denoted as the *capture ratio* [9, 10]. For most systems, concurrent transmissions in adjacent cells will cause SINR level to drop below the capture ratio. Two types of solutions are available to this problem: 1.) lowering the capture ratio or 2.) collision resolution based random access. The first solution, i.e., lowering the SINR threshold, has been adopted in systems such as HDR [11], where some sort of coding/spreading is employed in order to allow capture at the highest interference level. The price paid is a reduction in achievable peak rate. The second solution relates to the well known random access scheme [12]. Since SINR fluctuates rapidly in bursty traffic conditions, packet transmission can statistically take advantage of periods in which the SINR is above the capture ratio. When this happens, the packet is correctly received. Otherwise, packets are retransmitted. In practice, the ALOHA random access scheme can be used to solve "contentions" among transmissions of different cells. If the traffic is adequately low, and a retransmission scheme is implemented, a complete reuse of the bandwidth can be achieved. The advantage of this approach is that bandwidth is wasted only when there is a collision, as opposed to the worst-case limited strategy, where bandwidth is always used sub-optimally.

The first scheme essentially ensures the circuit-switch performance by adapting to the worst-case SINR. The second scheme has superior performance when the aggregate traffic is low, but will cause excessive delay when traffic load is heavy. The advantages and weakness of the both schemes motivate us to combine these two schemes together. The main contribution of this work is a distributed rate adaptive packet access (DRAPA) scheme which possesses the advantages of both rate adaptation and distributed random access schemes. In particular, DRAPA allows MS to transmit packets in a random access fashion independent of the activity of other cells. The packet code rate is adjusted according to the interference level and the interference traffic rate. Adaptive coding/modulation has been proposed for link layer adaptation based on direct channel information [13] or indirect channel information by combining with some modified ARQ schemes [14]. However, these link layer approaches do not take the characteristics of interference into consideration and are only suitable for slowly varying channels. The DRAPA scheme on the other hand, performs rate adaptation based on the channel and traffic condition of the interfering cells, so that it can adapt to the fast changing interference effectively. The DRAPA scheme subsumes the two old schemes as the extreme cases, and has superior performance over the old schemes in terms of throughput and stability.

The remainder of the chapter is organized as follows: Section 2 describe the DRAPA scheme and system assumptions. Section 3 provides the throughput analysis of the DRAPA scheme. Section 4 studies some special cases where there are only a limited number of dominant interference. Section 5 evaluates the performance of DRAPA scheme with simulations.

2 DRAPA Model and Assumptions

We consider a multi-cell network where the mobile-to-base-station link (uplink) is modeled as a multiple access system with all the cells sharing the same frequency bandwidth (Figure 2). DRAPA is implemented for the multicell medium access control (MAC). In order to describe DRAPA and evaluate its capacity, a simplified model is adopted here. We assume that BSs are at the center of the cells, and equiped with omni-directional antennas. All cells have the same radius R. In each cell, only one MS can transmit at a time in a traffic channel (e.g. FDMA, TDMA), therefore contentions among MSs in the same cell are avoided. The MSs in each cell are uniformly distributed. The user density in each cell is given by

$$f(x,y) = \frac{1}{\pi R^2}, \quad f(r) = \frac{2r}{R^2}.$$

For simplicity, we assume that packet transmissions in different cells are slot based, so that transmissions in different cells overlap completely.

Several statistical models have been proposed to model the stochastic behavior of the signal amplitude and power [15, 16]. We consider the channels affected by the Rayleigh fading, log-normal shadowing fading and pass loss. The received power W is given by:

$$W = \alpha^2 10^{0.1\rho} A r^{-\eta} W_T \tag{1}$$

where α^2 is Rayleigh fading factor, ρ is lognormal attenuation in decibels, ,η is pass loss exponent and W_T is transmitted power.

In packet networks, the interfering MSs may not transmit all the time. The probability for a cell to transmit at a given slot is determined by the traffic load G. We use a binary random variable x_i to represent the state of the MS in the ith cell. It takes value 1 if the MS is transmitting, and 0 otherwise. We have $P\{x_i = 1\} = G$. Also assume that the received power of the ith MS is W_i. Then the multiple access interference (MAI) is:

$$I_0 = \sum_{i=1}^{N} x_i W_i, \tag{2}$$

and the SINR of the considered MS is:

$$SINR_0 = \frac{W_0}{I_0 + \sigma_0^2} = \frac{W_0}{\sum_{i=1}^{N} x_i W_i + \sigma_0^2}. \tag{3}$$

In most cases, N, the total number of interferences, is small since only the adjacent cells have significant contribution to the interference level. From the above expression, we can see that the interference level may vary significantly at different slots because of the varying number of interferes as shown in Figure 3.

For any given coding scheme, if SINR drops below certain level, high packet error rate (PER) will significantly reduce the system throughput. To increase SINR tolerance, the code rate must be reduced. This is a trade off between outage probability and code rate. In traditional cellular networks, one of the key parameters is outage probability. The code is designed to accommodate certain outage probability assuming all the interfering MSs are active. Random access schemes, on the contrary, take advantage of the idle period of the interfering MSs. So the code is designed only based on background noise. In the presence of interference, there is a collision and the packets are retransmitted. It is well known that the random access scheme performs well when the aggregate traffic is low. However, when traffic is heavy, the throughput is reduced by the excessive retransmissions. The proposed DRAPA scheme combines the two schemes together so that packets are transmitted in an ALOHA based random access scheme, and at the same time the code rate is adjusted according to the co-channel users' power $W_0, W_1, W_2, \ldots, W_N$ and traffic rates $G_0, G_1, G_2, \ldots, G_N$ (note: instantaneous rate adaptation is improbable). By making packet code rate adjustable, MSs can optimally choose their code rate according to the interference level and traffic condition, so that the system throughput is maximized. More specifically, the DRAPA performs the follows:

1. Each BS exchanges with other BSs the number of co-channel MSs and their respective traffic rates $G_0, G_1, \ldots, G_N$.
2. The BS estimates the power level $W_0, W_1, \ldots, W_N$ of the active MSs from received signal.
3. The BS determines code rate from a predetermined code set according to the traffic and interference condition, and sends it in the downlink channel.
4. The MS transmits at the desired code rate in an ALOHA fashion. If the packet failed, it is retransmitted.

It is important to point out that because the code rate change does not affect the signal strength and traffic rate of current cell, the code adaptation in the cells is independent of each other. So the DRAPA is indeed distributed and the information exchange between BSs is minimized.

For tractability in the subsequent analysis, we invoke the following assumptions concerning the system configuration.

- Each MS has slowy changing channel and slowly changing traffic rate.
- Each BS has the knowledge of the traffic rate G_i and received power W_i of all MSs.
- Packets have fixed number of symbols and variable code rates. The code rate is defined as information bits per symbol.

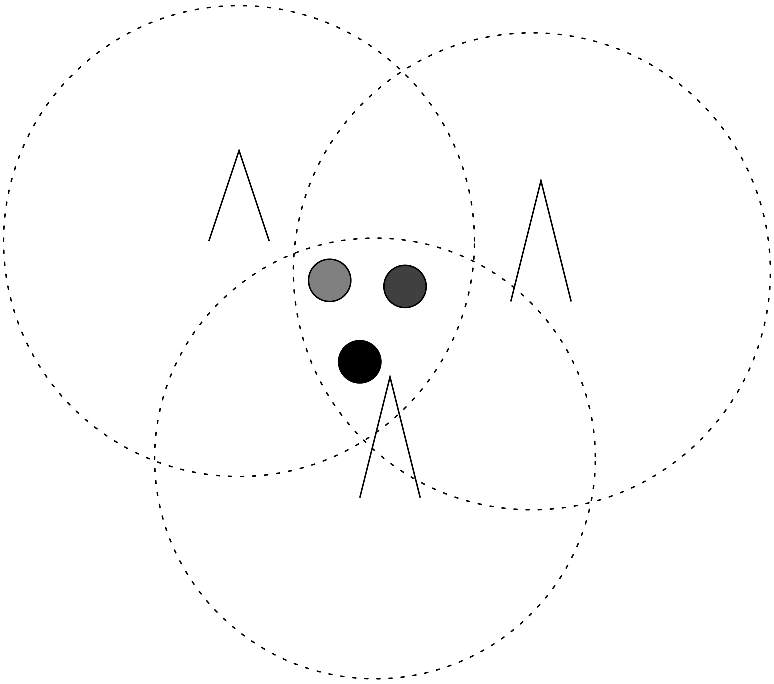

Figure 1: Multicell configuration for DRAPA

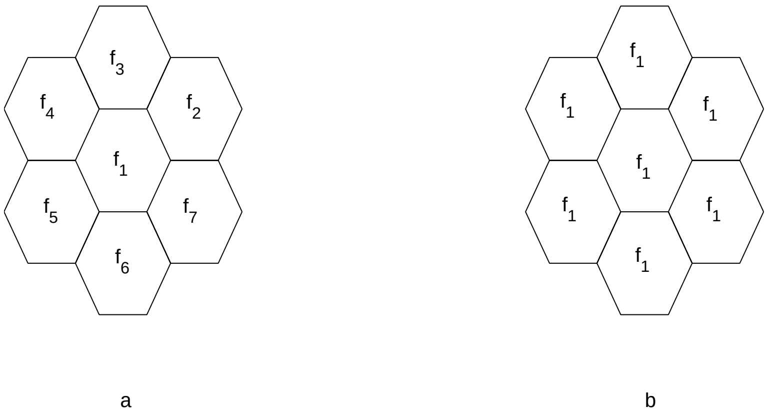

Figure 2: Multicell frequency reuse strategies: (a) Traditional reuse strategy, (b) DRAPA aggressive reuse strategy.

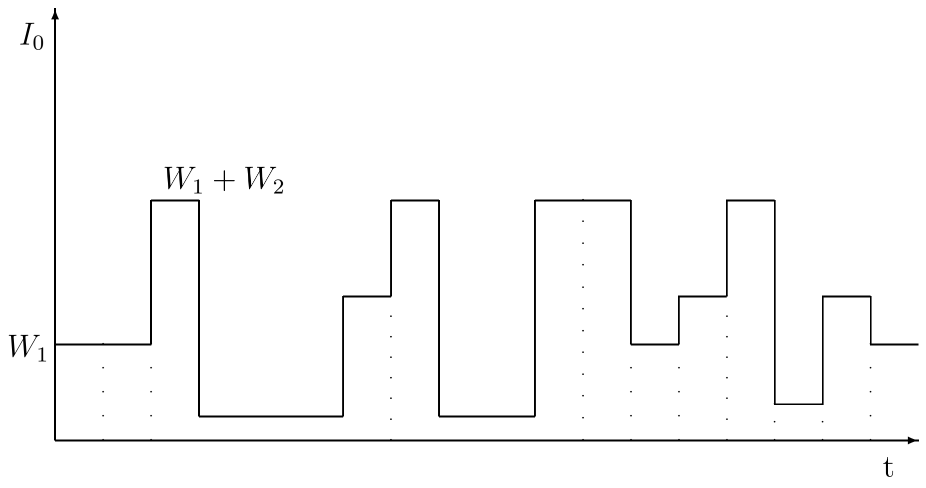

Figure 3: Multicell inter-cell interference variations

- Each MS's packet rate G_i is independent of its code rate $r_c^{(i)}$.

We assume slowly changing channel and traffic pattern so that the parameters can be estimated and exchanged. We allow some information exchange between BSs so that each BS has the knowledge of the traffic pattern of all MSs. The independent packet rate assumption seems counter intuitive. However, in OFDMA systems [17], one MS may be assigned multiple channels. Assume that one MS has average rate R_{tot}(bits/symbol) and is assigned n channels with code rates $\{r_c^{(1)}, r_c^{(2)}, \ldots, r_c^{(n)}\}$. Then for the ith channel, the traffic rate

$$G_i = E\{x_i\} = \frac{R_{tot}}{\sum_{k=1}^{n} r_c^{(k)}}.$$

Where x_i is a binary random variable which takes 1 if the channel is transmitting and 0 otherwise. So the change of code rate $r_c^{(i)}$ does not significantly affect G_i when n is large.

3 Throughput Analysis

The key to DRAPA is that the packet code rate selection depends on SINR variation, which is a function of the received power and traffic pattern. We shall first derive the SINR distribution for the MS interested. In the following, we use index "0" to represent the signal of interest and index "i" to represent the interference from cell $i, i \neq 0$. According to the model in the previous section, the probability, P, that the packet under consideration is above certain SINR d, is given by:

$$P(d) = P\left[\frac{W_0}{\sum_{i=1}^{N} x_i W_i + \sigma_0^2} \geq d\right] \tag{4}$$

x_i is a binary random variable which takes value 1 if a station is transmitting in cell i, and 0 otherwise. Given the number of inferences N and the received power W_i and traffic rate parameter x_i of the ith MS, the SINR distribution can be calculated.

If omni-directional antennas are used at the BSs, the locations of MSs are circular symmetric, i.e., the distributions of the received power of all the MSs with same distance to the BS are the same, regardless of their angles. The SINR is determined by two factors: 1.) signal strength; 2.) interference level. The signal strength is related to the location and fading pattern. The interference is determined by the interfering MSs location, fading pattern and traffic load. These two factors are mutually independent.

The interference can be randomly distributed [18]. If we only consider the interferers from the neighboring cells, then the maximum number of interferes is $N = 6$. Let the cell radius be R, then the interfering r_is are evenly distributed in the ring $[R, 3R]$. And x_i is binomial distribution with $P\{x_i = 1\} = G_i$. For simplicity, we assume $G_0 = G_1 = \ldots = G_N = G$. $P(d)$ as a function of G can be rewritten as:

$$P(d,G) = \sum_{k=1}^{N} C_N^k G^k (1-G)^{N-k} P\left[\sum_{i=1}^{k} W_i \leq \frac{W_0}{d} - \sigma_0^2\right] + (1-G)^N u(\frac{W_0}{\sigma_0^2}) \tag{5}$$

Define

$$\psi_k(d) = P\left[\sum_{i=1}^{k} W_i \leq \frac{W_0}{d} - \sigma_0^2\right] \tag{6}$$

as the SINR distribution where there are k out of N active MSs. Further denote $f_i(w_i)$ and $F_i(w_i)$ as the pdf and cdf of the received power distribution of the ith MS at the 0th BS respectively. We have:

$$\psi_k(d) = P\left[\sum_{i=1}^{k} W_i \leq \frac{W_0}{d} - \sigma_0^2\right] = \int_0^\infty dw_1 \ldots \int_0^\infty dw_k [1 - F_0(d\sum_{i=1}^{k} w_i + d\sigma_0^2)] \prod_{i=1}^{k} f_i(w_i) \tag{7}$$

Consider the channel model given in equation (1), we have:

$$F_i(w_i) = P\left[\alpha_i^2 10^{0.1\rho_i} r_i^{-\eta} \leq w_i\right] \tag{8}$$

By inserting (8) into (7), we can immediately calculate the SINR distribution with k active interference under channel model (1). The detailed analysis can be found in [10]. There are abundant studies on the link performance of cellular networks. Although stochastic occupation of nearby co-channel cells according to the traffic laws by Erlang was included in some studies [9, 10], most analysis have been limited to outage probabilities in continuous voice communication [15, 16, 19], where MSs are always transmitting. Fixed coding scheme is predetermined based on the outage probability analysis. However, the outage probability may not be an appropriate criterion for packet networks. In packet networks, messages lost due to interference or channel fading can simply be retransmitted. In this sense, throughput and delay are more important performance measures than outage probability. One of the key parameters is the packet error rate (PER). The PER is a decreasing function of SINR, and depends on the degree of error protection. For a given packet coding scheme, denote $p_e(d)$ the PER at given SINR d, and $f_s(d)$ the pdf of SINR distribution. Then the average PER is given by

$$P_e = \int_0^\infty p_e(x) f_s(x) dx. \tag{9}$$

In DRAPA scheme, code rate is adaptively chosen so that the throughput is maximized. However, because the information bits in a packet may vary with code rate adaptation, the traditional packet throughput can not adequately reflect the DRAPA performance. In order to evaluate the performance of the DRAPA scheme, we redefine the throughput as the product of packet throughput (packet success rate) and the packet code rate, i.e., $S = r_c(1 - P_e)$. This is in fact a measure of bandwidth efficiency in packet networks. To simplify the analysis, we assume that there exists a class of codes with continuously adjustable code rate. For a given code rate r_c, there is a SINR threshold d_c such that if $d \geq d_c$, all the packets with code rate r_c can be successfully decoded. Otherwise, the packets are in error and have to be retransmitted. This is in fact the ideal packet capture model [1] widely used in analytical studies. The SINR threshold d_c is the so-called capture threshold which enables perfect capture above the threshold and total loss below the threshold. Assume that code $\{r_c, d_c\}$ is used, under the perfect capture model, $P_e = 1 - P(d_c, G)$, and the corresponding throughput is:

$$S(r_c, G) = G r_c P(d_c, G) \tag{10}$$

In DRAPA, we want to find out the optimal code $\{r_c, d_c\}$ so that $S(d_c, G)$ is maximized. Denote the optimal code rate r_o, we have

$$r_c \frac{\partial P(d_c, G)}{\partial d_c} \frac{\partial d_c}{\partial r_c} + P(d_c, G)\Big|_{r_c = r_o} = 0 \tag{11}$$

By solving the above equation, we can obtain the optimal code rate r_o. Figure 4 and 5 show the SINR and throughput distribution in a cell as the function of distance to BS r and traffic rate G.

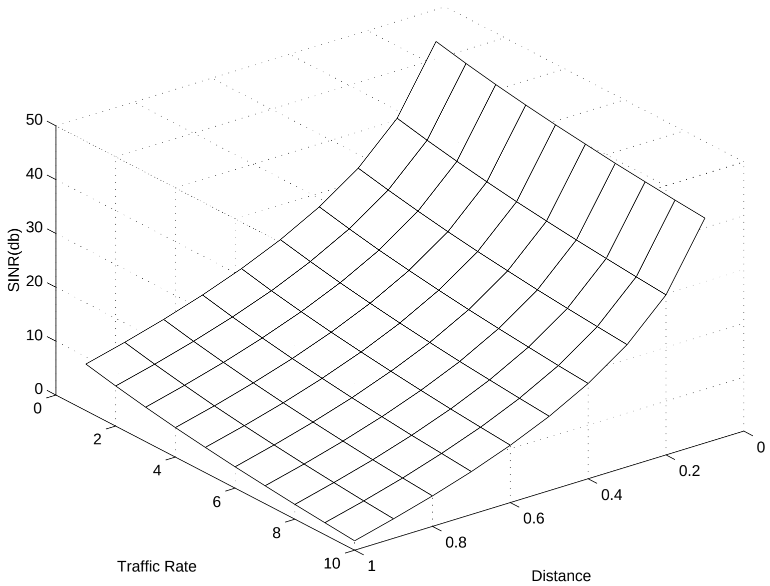

Figure 4: Multicell SINR distribution

By now we assume that the received signal strength of each MS is a random variable obeys certain channel model. However, if the channel changes slowly, it is possible for us to estimate the signal strength. With the knowledge of the signal and interference strength, we can better adapt to the fast changing SINR. Assume we have the knowledge of the all the signal and interference strength, e.g. $W_0, W_1, \ldots, W_N$, then there are 2^N possible interference states with SINRs $\{d_1, d_2, \ldots, d_{2^N}\}$. The probability of the states are $\{\pi_1, \pi_2, \ldots, \pi_{2^N}\}$. For a given code, it can guarantee perfect capture in some states. In order to have perfect capture in more states, the code rate must be reduced. This is a trade off between the code rate and outage probability. The code rate and outage probability can be related by the following theorem:

Theorem 1 *Assume the SINRs* $\{d_1, d_2, \ldots, d_k, \ldots, d_{2^N}\}$ *are sorted in descending order for states* $\{\pi_1, \pi_2, \ldots, \pi_k, \ldots, \pi_{2^N}\}$, *and the code rate* $r(d)$ *is monotonically increasing as a function of* $SINR$ d. *For a given outage probability* δ_0, *if* $\sum_{i=1}^{k-1} \pi_i \leq 1 - \delta_0 \leq \sum_{i=1}^{k} \pi_i$ *then the code with outage probability* $\delta \leq \delta_0$ *has a rate* $r_0 \leq r_c(d_k)$.

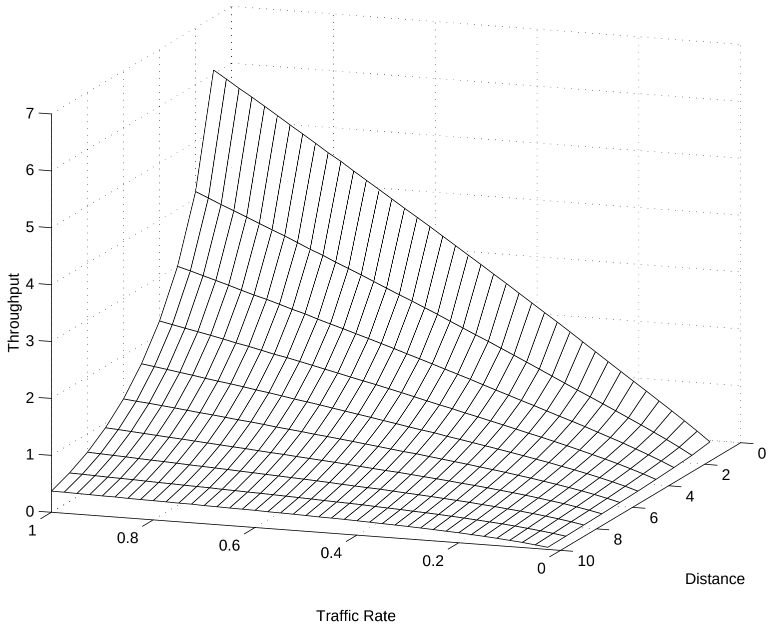

Figure 5: Multicell throughput distribution

The proof of the theorem is straight forward. Because the system has 2^{N-1} states, it has 2^{N-1} possible outage probability $\delta_1, \delta_2, \ldots, \delta_{2^{N-1}}$. The maximum code rate under each outage probability is denoted as $r_1, r_2, \ldots, r_{2^{N-1}}$. We can calculate the throughput for all the code selections:

$$S_i = r_i G_i (1 - \delta_i). \tag{12}$$

The DRAPA chooses the code which maximizes the throughput S_i,

$$r_{opt} = \{r_i | S_i = max\{S_k, k \in [1, 2, \ldots, 2^{N-1}]\}\} \tag{13}$$

Of all the possible states, there are two special cases. The first is that there is no interfering MS transmitting. This state has the highest SINR. The traditional ALOHA assumes a successful transmission only when there is no other simultaneous transmissions. It chooses the highest code rate and only operates in the interference free state. The second is that all MSs are transmitting. This case has the lowest SINR. The zero outage tolerance scheme guarantees transmission success in any state. It must choose the code rate according to the lowest SINR. The traditional cellular networks usually allow some degree of outage probability, but the analysis is the same as the zero tolerance scheme. The throughput of the ALOHA-based scheme and the zero outage scheme is denoted as S_a and S_w respectively.

$$S_a = Gr(d_1)\pi_0 \tag{14}$$

$$S_w = Gr(d_{2^{N-1}}) \tag{15}$$

They are both the special cases of the DRAPA code selection. DRAPA is guaranteed to outperform the both schemes. In DRAPA the code rate is adaptively adjusted according to the SINR and traffic condition. Such an adaptation is distributed. It depends on the interference strength and traffic load. But all cells choose their code rates independently and do not affect each other. Such property of code rate adaptation is extremely desirable for multi-cell systems, because the information exchange for rate adaptation is minimized. Although in practical systems, the rate adaptive codes may not follow the perfect capture assumption, we can group the states with close SINR together so that the distance between the groups are far enough to apply different code rates.

4 Special Cases with Limited Number of Interferences

In order to quantify the performance improvement, in this section we will study the system with only limited number of interfering MSs. In practical systems, especially when directional antennas are implemented, there are only 1 or 2 dominant interference. Therefore the cases that are of most interest are:

1. Two mutual interfering cells ($n = 2$),
2. Three mutual interfering cells ($n = 3$).

The code selection strategy and throughput performance evaluation are described below.

4.1 Two-Cell Case

Consider the case where there is only one dominant interference to the MS of interest. We label the two cells as 1 and 2. Assume the transmission probabilities of the ith cell is G_i. The received power of the ith cell if the jth cell is transmitting is W_{ij}. For each cell, the channel has two states. We define State S_1 as no interference from the other cell, and State S_2 as with interference from the other cell. The probability of the two states depends on the traffic load of the other cell. We

States	Cell 1		Cell 2	
	SINR	Probability	SINR	Probability
S_1	$\frac{W_{11}}{\sigma^2}$	$1 - G_2$	$\frac{W_{22}}{\sigma^2}$	$1 - G_1$
S_2	$\frac{W_{11}}{W_{12}+\sigma^2}$	G_2	$\frac{W_{22}}{W_{21}+\sigma^2}$	G_1

Table 1: States of a 2-Cell system

define the probability of the ith cell in state j as π_{ij} and the corresponding SINR in this state as d_{ij}. Table 1 lists the states and their corresponding probability and SINR for both cells.

Since the cells have multiple states with different SINRs, rate adaptive codes can be chosen to optimize the performance. Consider cell 1 as an example. If we choose the highest code rate which only guarantees perfect capture in state S_1, the code rate is $r_c(d_{11})$. The throughput is:

$$S_{11} = G_1 r_c(d_{11})\pi_{11} = G_1 r_c(d_{11})(1 - G_2). \tag{16}$$

One the other hand, the code that guarantees perfect capture under both states has a lower rate $r_c(d_{12})$, and the corresponding throughput is

$$S_{12} = G_1 r_c(d_{12}). \tag{17}$$

S_{11} is a decreasing function of G_2. It varies with the traffic condition in cell 2. On the other hand S_{12} is independent of the traffic condition in cell 2. We have $S_{12} \geq S_{11}$ if

$$G_2 \geq 1 - \frac{r_c(d_{12})}{r_c(d_{11})}. \tag{18}$$

Similarly in cell 2, $S_{22} \geq S_{21}$ if

$$G_1 \geq 1 - \frac{r(d_{22})}{r(d_{21})}. \tag{19}$$

Clearly, even the signal and interference power are known, the code selection for each cell still depends on other cells' traffic load. This again confirms the importance of traffic-dependent

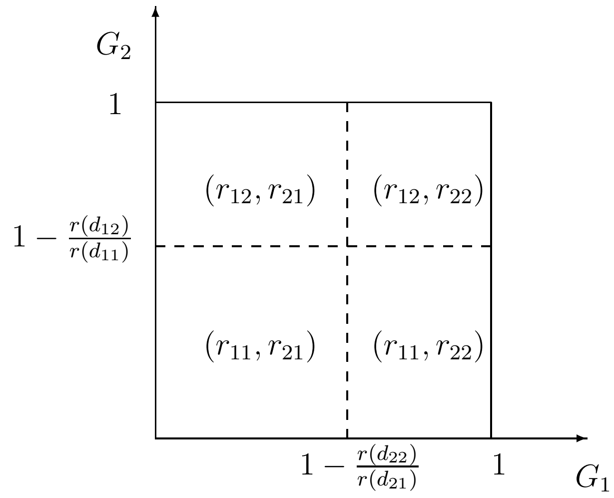

Figure 6: Code selection of two users case

code selection. For the two-cell case, the above two coding schemes represents the two extreme scenarios: $r_c(d_{11})$ is for pure ALOHA based random access independent of the interference, $r_c(d_{12})$ is for worst-case performance guaranteed circuit switched network. Equations (18) and (19) show that both fixed coding schemes are likely to be suboptimal for a given traffic pattern. The traffic based code rate adaptation is necessary to improve the throughput for packet network. The region of the code combinations of the two cells in the traffic rate plane is shown in Figure 6. It is shown that rate adaptation is required only when the traffic load crosses certain threshold. which means adaptation only occurs when traffic pattern significantly changes. This significantly relaxes the requirement on the traffic rate estimation, and the frequency of rate adaptation.

4.2 Three-Cell Case

In the 3-cell case ($n = 3$), there are 2 interfering MSs. Each interfering MS has ON and OFF states, so the interference has 4 states. The SINR and probability of the states in each cell are listed in Table 2, where we denote $\bar{G}_i = 1 - G_i$.

For the MS of interest, we can choose 4 sets of codes with different rate to guarantee perfect capture in 4 states. Without loss of generality, we assume that $d_{12} \geq d_{13}$. Denote the code rate that covers the first k states as $r_c(d_{1k})$. The throughput corresponding to the 4 code rates are:

$$S_{11} = G_1 r_c(d_{11})\pi_{11} = G_1 r_c(d_{11})(1 - G_2)(1 - G_3) \quad (20)$$

$$S_{12} = G_1 r_c(d_{12})(\pi_{11} + \pi_{12}) = G_1 r_c(d_{12}) G_2 (1 - G_3) \quad (21)$$

$$S_{13} = G_1 r_c(d_{13})(\pi_{11} + \pi_{12} + \pi_{13}) = G_1 r_c(d_{13}) G_3 (1 - G_2) \quad (22)$$

States	Cell 1		Cell 2		Cell 3	
	SINR	Probability	SINR	Probability	SINR	Probability
S_1	$\frac{W_{11}}{\sigma^2}$	$\bar{G}_2\bar{G}_3$	$\frac{W_{22}}{\sigma^2}$	$\bar{G}_1\bar{G}_3$	$\frac{W_{33}}{\sigma^2}$	$\bar{G}_1\bar{G}_2$
S_2	$\frac{W_{11}}{W_{12}+\sigma^2}$	$G_2\bar{G}_3$	$\frac{W_{22}}{W_{23}+\sigma^2}$	$G_3\bar{G}_1$	$\frac{W_{33}}{W_{31}+\sigma^2}$	$G_1\bar{G}_2$
S_3	$\frac{W_{11}}{W_{13}+\sigma^2}$	$G_3\bar{G}_2$	$\frac{W_{22}}{W_{21}+\sigma^2}$	$G_1\bar{G}_3$	$\frac{W_{33}}{W_{32}+\sigma^2}$	$G_2\bar{G}_1$
S_4	$\frac{W_{11}}{W_{12}+W_{13}+\sigma^2}$	G_2G_3	$\frac{W_{22}}{W_{21}+W_{23}+\sigma^2}$	G_1G_3	$\frac{W_{33}}{W_{31}+W_{32}+\sigma^2}$	G_1G_2

Table 2: States of a 3-Cell system

$$S_{14} = G_1 r_c(d_{14}) \tag{23}$$

Same as in the 2-cell case, we can choose the code rate to maximize the cell throughput according to the traffic conditions in these cells. However, we can further simplify the code adaptation based on the relative strength of the two interferences. If $d_{12} \approx d_{13}$, then $r_c(d_{12}) \approx r_c(d_{13})$. So the two states S_2 and S_3 can used the same code and thus can be merged. On the other hand, if $d_{12} \gg d_{13}$, it actually reduced to a 2-cell scenario where there is only one dominant interference. This leads to $d_{13} \approx d_{14}$, and thus sate S_3 and S_4 can be merged. In both scenarios, the number of states can be reduced to 3, and thus simplify the rate adaptation. In the following, we consider the two cases separately.

- $d_{12} \approx d_{13}$,

$d_{12} \approx d_{13}$ means that the interference strength from two cells are almost the same, so that state S_2 and S_3 can be merged. We denote the merged state as S_3' Accordingly, the three codes corresponding to state S_1,S_3' and S_4 are $r_1 = r_c(d_{11}), r_2 = r_c(d_{13}), r_3 = r_c(d_{14})$, and corresponding throughput are:

$$S_{11} = r_1 G_1 (1 - G_2)(1 - G_3) \tag{24}$$

$$S_{13}' = r_2 G_1 (1 - G_2 G_3) \tag{25}$$

$$S_{14} = r_3 G_1 \tag{26}$$

In DRAPA, the code is chosen to maximized the throughput for given traffic condition. The optimal throughput is $S_o = \max\{S_{11}, S_{13}', S_{14}\}$.

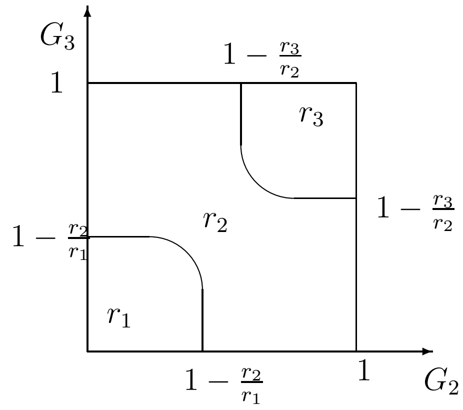

Figure 7: Code selection, 3 cells ($d_{12} \approx d_{13}$)

$$S_o = \begin{cases} S_{11} & (G_2 - \frac{r_1}{r_1+r_2})(G_3 - \frac{r_1}{r_1+r_2}) \geq (\frac{r_2}{r_1+r_2})^2 \\ S_{14} & G_2 G_3 \geq 1 - r_3/r_2 \\ S_{13}^{'} & Otherwise \end{cases} \quad (27)$$

Equation (27) shows that the optimal code selection depends on the traffic load G_2, G_3 in the other two cells. Each code has its operation region on the plan (G_2, G_3) as shown in Figure 7.

- $d_{12} \gg d_{13}$.

$d_{12} \gg d_{13}$ means that one of the two interferences dominates. Consequently, the states S_3 and S_4 have almost the the same code rate and thus can be are merged. We denote the remaining three states as S_1, S_2 and $S_4^{'}$. Accordingly, the three code rates are $r_1 = r_c(d_{11}), r_2 = r_c(d_{12}), r_4 = r_c(d_{14})$, and corresponding throughput are:

$$S_{11} = r_1 G_1 (1 - G_2)(1 - G_3) \quad (28)$$

$$S_{12} = r_2 G_1 (1 - G_3) \quad (29)$$

$$S_{14}^{'} = r_4 G_1 \quad (30)$$

$$(31)$$

Let the optimal throughput $S_o = \max\{S_{11}, S_{12}, S_{14}^{'}\}$. Then S_o at different traffic condition $\{G_2, G_3\}$ is given has follows:

$$S_o = \begin{cases} S_{11} & G_2 \leq 1 - \frac{r_2}{r_1} \;\; and \;\; (1 - G_2)(1 - G_3) \geq \frac{r_4}{r_1} \\ S_{12} & G_2 \geq 1 - \frac{r_2}{r_1} \;\; and \;\; G_3 \leq 1 - \frac{r_4}{r_2} \\ S_{14}^{'} & Otherwise \end{cases} \quad (32)$$

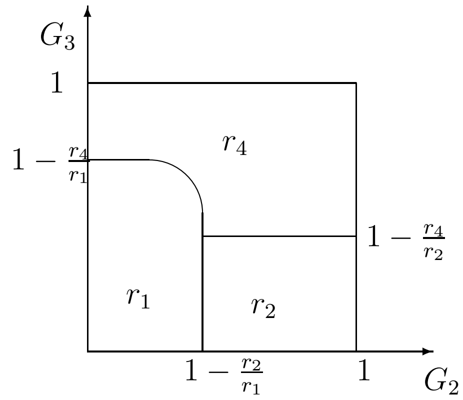

Figure 8: Code selection, 3 cells ($d_{12} \gg d_{13}$)

The operation region of different codes on the plan (G_2, G_3) is shown in Figure 8.

The above analysis shows that the code rate of each MS is determined by the signal strength and traffic rate of all the active MSs. Code rate is selected to maximize the cell throughput. It is important to point out that because code rate change does not affect the signal strength and traffic rate of the current cell, the code rate adaptation in each cell is independent. The code rate adaptation actually maximizes the total throughput of all cells. With ALOHA random access and outage probability bounded rate adaptation as its special cases, the DRAPA maximizes the total throughput and is stable in any traffic condition. In next section, we evaluate the performance of DRAPA by simulations.

5 Simulation Results

In the previous analysis, we assume that the code rate is continuously adjustable with a perfect capture ratio. In pratical systems, a set of rate-compatible punctured convolutional (RCPC) codes [20] are combined with variable modulation constellation size to provide good bit rate granularity with regard to the SNR variation. In RCPC, the different rates are constructed by puncturing a low rate mother code to higher rates. Both adaptive coding and modulation (ACM) are required for good system performance since adaptive coding or modulation alone cannot adequately represent the desired rate granularity [21]. Table 3 lists the ACM schemes we used for rate adaption. The link performance of the ACM schemes listed in Table 3 is shown in Figure 9, where each packet has 512 symbols and ideal ARQ is assumed. The figure displays the SINR required to achieve a number of information bits per FEC coded/modulated symbol. For the ith ACM format, the bits per symbol as a function of SNR $b_i(d)$ is the product of code rate r_i and the packet success rate.

Constellation	Code Rate	Information bits/symbol
QPSK	1/2	1
QPSK	3/4	1.5
8PSK	2/3	2
16QAM	3/4	3
16QAM	uncoded	4

Table 3: Adaptive coding/modulation formats

$$b_i(d) = r_i(1 - PER_i(d)) \tag{33}$$

The best performance is obtained at each SINR by selecting the ACM format that is closest to the vertical axis. A hypothetical curve passing through all of these points will be called the desired rate-set curve. The selected formats listed in Table 3 adequately represent the desired rate curve. In DRAPA, the ACM format is selected for each MS based on the measured channel quality and traffic condition. Links with high quality are given higher order modulation and/or high code rate to improve system capacity, while links with low quality are given a more robust modulation/coding combination to improve reliability.

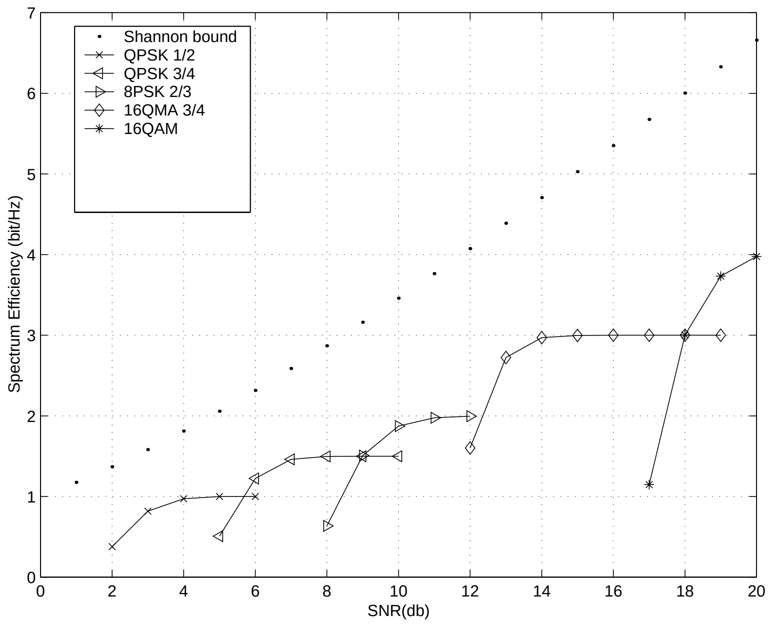

Figure 9: Normalized throughput in AWGN for different RCPC codes

Simulations are carried out to evaluate the performance of the code rate adaption scheme. In the simulations, we assume that the channel is subject to 6db lognormal shadow fading, i.e. $\alpha = 1$, $\rho = 0.6$. Because the MSs close to the BS are not affected by the interference, we are only interested in the MSs in region $[R/2, R]$, where R is the cell radius. We first compare the performance of DRAPA with the aloha and worst case performance limited approaches in 2-cell and 3-cell systems. Figure 10 compares the throughput performance of a 2-cell system. We can see that the ALOHA scheme performs quite well when the traffic is adequately low. However, as the traffic load increases, its throughput drops sharply. The worst case performance bounded scheme on the other hand, guarantees steady performance in heavy traffic while has low throughput in low traffic load beause of the over designed SINR margin. The DRAPA scheme, adaptively adjusting code rate according to the traffic condition, is able to keep high throughput in any traffic condition.

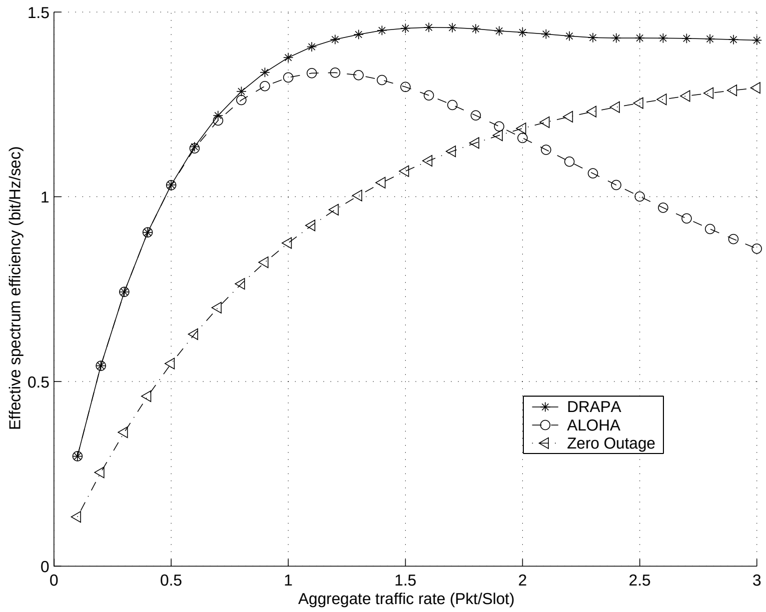

Figure 10: Throughput comparison of 2-cell system

Figure 11 compares the throughput performance of a 3-cell system. It shows similar performance to the 2-cell system. However, because of the increased interference, the sepectrum efficiency is reduced. Furthermore, because there are more states in the 3-cell system, the performance improvement of DRAPA is more significant.

Figure 12 compares the performance of DRAPA scheme with that of other frequency reuse strategies, e.g. $C = 3, 7$. It shows that with DRAPA, a significant improvement in spectrum efficiency can be achieved. And at the same time DRAPA has the advantage that each cell has the access to the whole bandwidth. Figure 12 also shows that although the ALOHA scheme allows full bandwidth access, the servere inter-cell interference results in poor throughput. This further

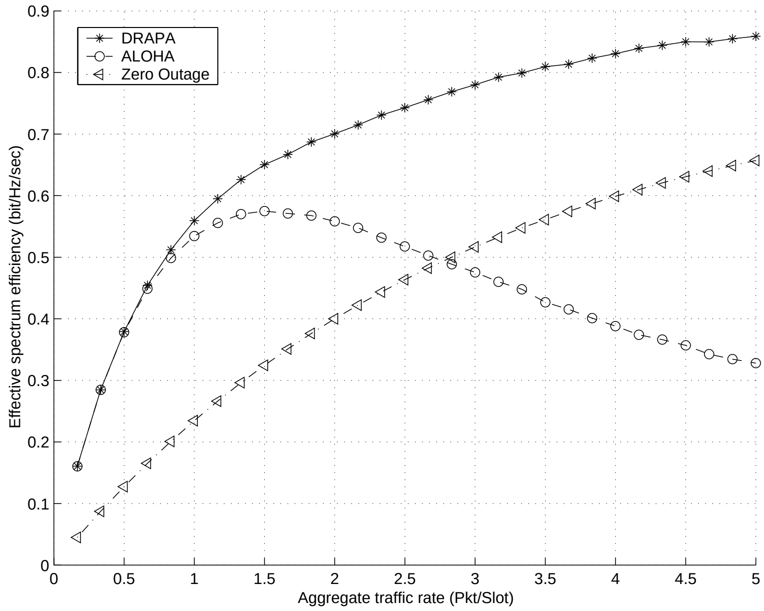

Figure 11: Throughput comparison of 3-cell system

comfirms that the rate adapation is necessary in the aggressive frequency reuse system ($C = 1$).

6 Conclusion

In this chapter, we proposed a distributed rate adaptive packet access (DRAPA) scheme which inherits the advantages of both the circuit switch based rate adaptation and packet switch based random access. DRAPA allows mobile stations to transmit packets in random access mode independent of the activity of other cells, while the pakcet code rate is adjusted according to the interference level and traffic rate, so that the retransmisson is controlled at an acceptable level. The code rate selection of each cell is independent of others, so that the inter-cell information exchange is minimized. The DRAPA subsumes the ALOHA random access scheme and the worst case limited scheme as the extreme cases, and has superior performance over the traditional schemes in terms of throughput and stability. So, the DRAPA scheme is highly desirable for the future wireless packet networks.

References

[1] Jean-Paul M. G. Linnartz, "On the Performance of Packet-switched Cellular Netowrks for Wireless Data Communications, *Wirelss Networks*, **1**, 1995.

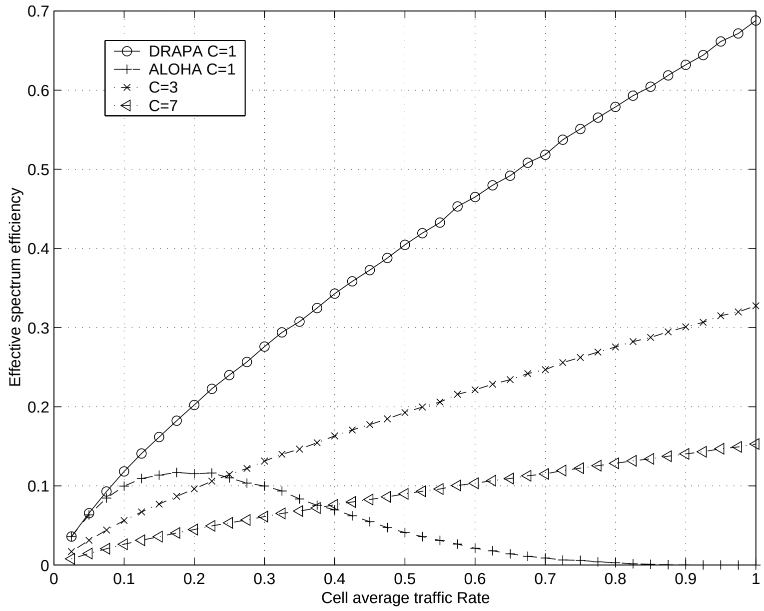

Figure 12: Throughput with different frequency reuse strategies

[2] Seong Rag Kim, Young Gyun Jeong, Jeong Goo Lee, and In-Kyeong Choi, “Incorporation of Adaptive Interference Cancellation into Parallel Interference Cancellation”, In *IEEE Proc. VTC'99*, pages 1242 –1245, 1999.

[3] C. U. Saraydar, N. B. Mandayam, and D. J Goodman, “Power Control in a Multicell CDMA Data System Using Pricing”, In *IEEE Proc. VTC'00*, pages 484 –491, 2000.

[4] B. A. Bjerke, J. G. Proakis, K. Lee, and Z. Zvonar, “A Comparison of GSM Receivers for Fading Multipath Channels with Adjacent and Co-channel Interference”, *IEEE Journal on Selected Areas in Communications*, **18**, November 2000.

[5] O. Gurbuz and H. Owen, “Dynamic Resource Scheduling Schemes for W-CDMA Systems”, *IEEE Communications Magazine*, **38**, October 2000.

[6] J. S. Blogh, P. J. Cherriman, and L. Hanzo, “Dynamic Channel Allocation Techniques Using Adaptive Modulation and Adaptive antennas”, *IEEE Journal on Selected Areas in Communications*, **19**, February 2001.

[7] Xuming Fang, Changqian Zhu, and Pingzhi Fan, “Greedy-based Dynamic Channel Assignment Strategy for Cellular Mobile Networks”, *IEEE Communications Letters*, **4**, July 2000.

[8] Z. Jiang, L. F. Chang, and N. K. Shankaranarayanan, “Providing Multiple Service Classes for Bursty Data Traffic in Cellular Networks”, In *IEEE Proc. INFOCOM'00*, pages 1087–1096, 2000.

[9] Flaminio Borgonovo, M. Zorzi, L. Fratta, V. Trecordi, and G. Bianchi, "Capture-Division Packet Access for Wireless Personal Communications", *IEEE Journal on Selected Areas in Communications*, **14**, May 1996.

[10] Michele Zorzi and Silvano Pupolin, "Outage Probability in Multiple Access Packet Radio Networks in the Presence of Fading", *IEEE Trans. on Vehicular Technology*, **43**, August 1994.

[11] Paul Bender, Peter Black, Matthew Grob, R. Padovani, N. Sindhushayana, and A. Viterbi, "CDMA/HDR:A Bandwidth-Efficient High-Speed Wireless Data Service forNomadic Users", *IEEE Communications Magazine*, **38**, July 2000.

[12] Norman Abramson, "The Throughput of Packet Broadcasting Channels", *IEEE Trans. on Communications*, **25**, January 1977.

[13] N. B. Mehta and A. Goldsmith, "Performance Analysis of Link Adaptation in Wireless Data Networks", In *IEEE Proc. GLOBECOM'00*, pages 1422–1426, 2000.

[14] Tan F. Wong Qian Zhang and James S. Lehnert, "Performance of a Type-II Hybrid ARQ Protocol in Slotted DS-SSMA Packet Radio Systems", *IEEE Trans on Communications*, **47**, February 1999.

[15] W. Gosling, "A Simple Mathematical Model of Co-channel and Adjacent Channel Interference in Land Mobile Radio", *IEEE Trans. on Vehicular Technology*, **29**, November 1980.

[16] D. C. Cox, "Cochannel Interference Consideration in Frequceny Reuse Small-coverage-area Radio Systems", *IEEE Trans. Communications*, **30**, 1982.

[17] Hujun Yin and Hui Liu, "An Efficient Multiuser Loading Algorithm for OFDM-based Broadband Wireless Systems", In *IEEE Proc. GLOBECOM'00*, 2000.

[18] X .Yang and A. P. Petropulu, "Joint Statistics of Interference in a Wireless Communication Link Resulted from a Poisson Field of Interferers", In *IEEE Proc.ICASSP'02*, 2002.

[19] A. Annamalai, C. Tellambura, and V. K. Bhargave, "Simple and Accurate Methods for Outage Analysis in Cellular Mobile Radio Systems - A Unified Approach", *IEEE Trans. on Communications*, **49**, February 2001.

[20] L. H. C. Lee, "New Rate-Compatible Punctured Convolutional Codes for Viterbi Decoding", *IEEE Trans. on Communications*, **42**, December 1994.

[21] Kevin Baum, Brian Classon, Kevin Cutts, and V. Desai, "Performance Analysis of an Adaptive OFDM Packet Data System", In *IEEE Proc. Broadband Communications'00*, pages 237–243, Zurich, 2000.