QoS–Constrained Information Theoretic Capacity Maximization in CDMA Systems

Ph.D. Candidacy Exam Presentation

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Transmission Power Assignment

- Capacity regulation in CDMA systems demands effective transmission power assignment.
  - For example, in DS/CDMA systems there is universal frequency reuse.
- There is need to designate transmission powers to the stations,
  - Given practical constraints,
  - Towards optimizing a properly–devised goal function.
- The major questions are,
  - What constraints will result in a practically–deployable system?
  - Are we able to accurately and efficiently solve the resulting problem?

Fixed–SNR Approach

- **Basic Approach**: Define a set of constraints and find the solution which satisfies all of them at equality.
  - **Classical Example**: Find the set of transmission powers which provide a given (often identical) signal to noise ratio (SNR) for all the stations in a cell.
  - Extensive work exists on fixed–SNR approach (examples discussed in the report).
  - The fixed–SNR can be implemented through open–loop power control by single stations using power messages (power up/power down).
  - Suitable for voice–only systems.
- Multimedia–enabled networks have shifted the problem into maximizing the aggregate capacity.

Capacity Maximization: The New Goal

- New systems need more control over the transmission rates.
  - Departure from solely eliminating the near–far effect.
- The aim is the maximization of the aggregate capacity of the system.

The Focus of this Research

- We focus on the reverse link (uplink)
  - Uplink is often the limiting link.
  - For comparison of the characteristics of this link with the forward link refer to the report.
- We concentrate on the traffic channels,
  - Due to the more demanding conditions they need to satisfy.
- We primarily focuse on the system at chip–level,
  - To comply with the history of the problem.
  - Extensions to symbol–level analysis are mentioned in the future directions.
- Here, capacity is defined as the rate of transmission of each station.
- The basic model used here considers a single–class system.
  - Extension to multiple–class systems will be given later.

Single Cell vs. Multiple Cell

- This thesis first considers single–cell systems, by assuming that,
  - Either there is only one cell in the system,
  - Or that the activity in other cells can be modeled as fixed interference to the current cell (details in the report).
- Efficient analysis of single–cell systems can potentially result in the extension of the work to multiple–cell systems.
  - To be discussed in the future directions.

Literature Review - Early Works

- *Knopp* and *Humblet* (1995) are among the first to work on system–wide information theoretic capacity of CDMA systems.
- *Hanly* and *Whiting* (1993) and *Hanly* and *Tse* (1999) developed the idea for multi–user networks.
- *Kandukuri* and *Boyd* (2000), *Oh* and *Zhang* and *Wasserman* (2003), and *Jafar* and *Goldsmith* (2003) changed the focus from the set of all the capacities to the analysis of the aggregate capacity.
    - A major challenge is the mapping between the signal to interference ratio (SIR) and the capacity.

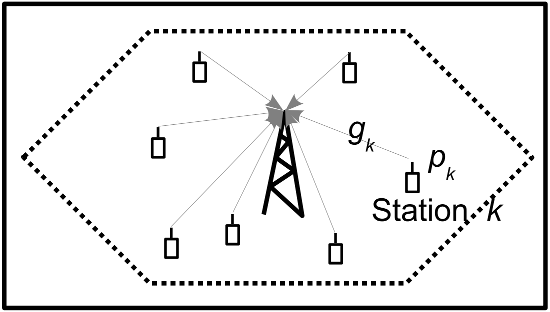
SIR–Capacity Mapping

- Earlier works assume sub–optimal coding,
  - In which case the SIR–capacity mapping is determined by the coding strategy.
- Coding strategies such as Turbo Coding make Shannon's bound practically achievable.
  - Here, the assumption of additive white Gaussian noise (AWGN) has been made.

Literature Review - Early Models

- **General Model**: Determine the transmission powers of the reverse link which maximize a capacity–oriented objective functions subject to different sets of constraints.
- For example, *Foschini* and *Miljanic* (1993), *Sung* and *Wong* (1999), and *Sung*, *Leung* and *Wong* (2000) work on minimizing the transmitted power subject to a minimum SIR requirement.
  - Suitable for fixed–SIR voice–only communications.
- *Sampath*, *Kumar*, and *Holtzman* (1995) limit the constraint to minimum guaranteed SNR and bounds on the individual transmission powers.
  - For minimizing the aggregate received power.
  - For maximizing the aggregate capacity.
- Yates (1995) minimizes the aggregate received power subject to power and SNR constraints.
- Similar work carried out by *Zender* (1992) and *Wu* (1999) in a stochastic framework.

Classical Single Cell (CSC)



- *Oh* and *Soong* (2003) put together a set of basic constraints.
  - This model will be addressed as the classical single cell (CSC).
  - Precise definition of the CSC will follow shortly.

Mathematics of the CSC - Model

- Capacity of a single point–to–point communication link,

$$C = B\log_2\left(1 + SIR\right).$$

  - B is the constant bandwidth and will be omitted.
- At the chip level, the SIR is equal to the SNR.
- With a background noise of I, the SIR for the i–th station is modeled as,

$$\gamma_i = \frac{p_i g_i}{I + \sum_{j=1, j\neq i}^{M} p_j g_j}$$

Mathematics of the CSC - Path Gains

- There are M mobile stations with reverse link gains of $g_1, \cdots, g_M$,
  - All located in the same cell and communicating with the same base station.
- The g_is only consider the path–loss,
  - The system is analyzed in time slots of T_s, where $T_s \gg \frac{1}{W}$ (W is the bandwidth).
  - The coherence time of the most rapidly varying channel is greater than T_s.
  - The typical time interval during which the shadowing factor in nearly constant for a mobile station is a second or more.
  - Therefore, in each time slot, g_is can be assumed to be constant, given that the run–time of the algorithm is significantly less than a second.

$$g_1 > \cdots > g_M.$$

Mathematics of the CSC - Constraints

- Maximum bound for the transmission power of the i–th station (p_i),

$$0 \leq p_i \leq p_{max}, \forall i.$$

- This constraint can be generalized, as discussed in the report.
- Minimum guaranteed SIR,

$$\gamma_i \geq \gamma, \forall i.$$

- Maximum aggregate received power,

$$\sum_{i=1}^{M} p_i g_i \leq P_{max}$$

.

Mathematics of the CSC - Objective Function

- Summation of the capacities of the stations.

$$C(\vec{\mathbf{p}}) = \log_2 \frac{\left(I + \sum_{j=1}^{M} p_j g_j\right)^M}{\prod_{i=1}^{M}\left(I + \sum_{j=1, j\neq i}^{M} p_j g_j\right)}.$$

- Decision variables of the optimization problem: $\vec{\mathbf{p}} = (p_1, \cdots, p_M)$.

Solving the CSC - The Classical Approach

- The search–space is of dimension M.
- *Oh* and *Soong* showed that the search can be limited to a multiply of M number of one–dimensional intervals.
- For that, they utilized a numerical optimization method.

Fairness Analysis

- As noted in the literature, analysis of the fairness of the CSC is necessary.
- Through this analysis, more constraints can be added to the problem, thus producing a solution with better properties.
- Measures of Fairness/Unfairness,
  - Subtractive Unfairness,

$$f = \max\{C_i\} - \min\{C_i\}.$$

  - Ratio Unfairness,

$$\tilde{f} = \frac{\max\{C_i\}}{\min\{C_i\}}.$$

  - Capacity–Share of the i–th station,

$$\tilde{C}_i = \frac{C_i}{C}.$$

  - C_i: Capacity of the i–th station.

Summary of Results

- In the next few slides, research done in this first stage of this work will be presented.
- First, the proposed method for solving the CSC will be presented.
- Then, the unfairness of the solution to the CSC will be presented.
- The addition of new constraints to the problem will be discussed.
- Approximation will be used in order to reduce the computational complexity of the solvers.
- Utility functions will be incorporated into the problem.
- The removed mathematical details can be found in the submitted report, and also the complete report available in author's webpage.

Solving the CSC: p_i–x_i Transformation

- the problem is rewritten in terms of x_is defined as,

$$x_i = \frac{p_i g_i}{I}.$$

- Resulting in,

$$\min \Phi(\vec{\mathbf{x}}) = \frac{\prod_{i=1}^{M}\left(1 + \sum_{j=1}^{M} x_j - x_i\right)}{\left(1 + \sum_{j=1}^{M} x_j\right)^M}.$$

- Given,

$$0 \leq x_i \leq l_i = \frac{p_{max}}{I} g_i, \forall i,$$

$$\frac{x_i}{1 + \sum_{j=1}^{M} x_j} \geq \varphi = \frac{\gamma}{\gamma + 1}, \forall i,$$

$$\sum_{i=1}^{M} x_i \leq X_{max}.$$

Solving the CSC: Analysis in Hyperplanes

- The problem is analyzed in the hyperplane defined as,

$$\sum_{i=1}^{M} x_i = T.$$

- The constraints reduce to,

$$T \leq X_{max}.$$

$$\varphi(1+T) \leq x_i \leq l_i, \forall i.$$

- **Theorem**: There can be no i and j for which in the solution, the value of $|x_i - x_j|$ can increase and all the constraints remain satisfied.

Solving the CSC: Closed–Form Solution

- **Theorem**: The solution to the CSC is as,

$$\vec{\mathbf{x}} = (l_1, \cdots, l_{k-1}, x_k, \varphi(1+T), \cdots, \varphi(1+T)).$$

- The problem reduces to finding k and x_k.
- **Theorem**: x_k must satisfy,

$$x_k \leq \max_k = \min \left\{ \begin{array}{l} l_k \\ (X_{max}+1)\left[1-(M-k)\varphi\right]-L-1 \\ l_M \frac{1-(M-k)\varphi}{\varphi} - L - 1 \end{array} \right\},$$

$$x_k \geq \min_k = \frac{\varphi(L+1)}{1-(M-k+1)\varphi}.$$

- **Theorem**: x_k has to accept either $\min_k$ or $\max_k$.
- The problem reduces to checking an order of M potential solutions (finite search space).

Solving the CSC: Proposed Algorithm

- For all k satisfying $M - \frac{1}{\varphi} + 1 < k < \frac{1}{\varphi} - \frac{1}{I_M} + 1$ do the followings,
  - Compute max_k and min_k.
  - If $max_k \geq min_k \geq 0$ then do the following lines for the two values of $x_k = min_k$ and $x_k = max_k$, separately. Store both Φ and the values of x_i for each trial.
    - Set up the solution and calculate the objective function.
- Find the best solution.

Computational Complexity: $\tau_{CSC} \leq 8M^2 + 20M + 10$ *(2ms of computation for* 100 *stations).*

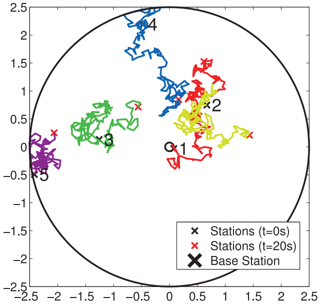
Nine times faster than the available method.

Unfairness of the CSC - Literature

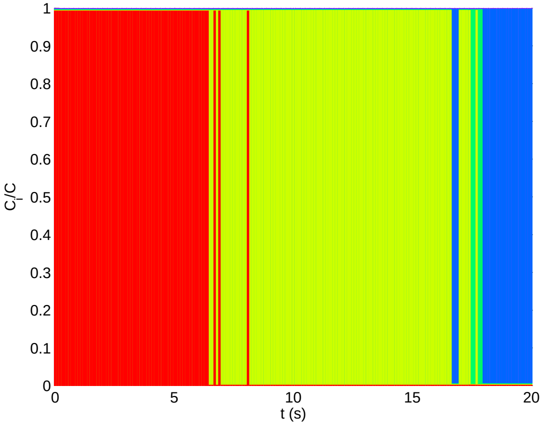
- In the CSC, typically, there is one single station transmitting at a capacity about fifty times as mush as the others.
- Also reported by *Oh* and *Zhang* and *Wasserman* (2003), *Jafar* and *Goldsmith* (2003), and others.
- The unfairness was one of the main motives for the addition of the minimum SIR by *Oh* and *Soong* (2006).
- One experiment will be presented here, more can be found in the appendix.

Unfairness of the CSC - Experiment

- Simulation of the movements of $M = 5$ stations in a cell where no hand–off happens.
- Based on *Jabbari* and *Fuhrmann* (1997).
- From $t = 0s$ to $t = 20s$, the system is solved every $dt = 100ms$.
- The pattern of the $\tilde{C}_i$s is presented here.
- More curves are available in the appendix.



Unfairness of the CSC - Results



Capacity–Share of the Stations in the Solution to the CSC.

New Single Cell (NSC)

- In the CSC, ratio unfairness can exceed one thousand.
- The aggregate capacity in the CSC declines as the number of the stations increases.
- The CSC offers a major chunk of the aggregate capacity to the closest station ($\tilde{C}_i > 90\%$).
  - This system is very unfair.
  - It is unknown if there exists any station capable of consuming such bandwidth.
  - The capacity offered to the "hot" station can decline drastically at any moment (detailed curves presented in the appendix).
- We suggest that the addition of a maximum capacity can resolve the issue.

$$C_i \leq \eta, \forall i.$$

New Single Cell (NSC) - The Solver

- **Theorem**: Defining $\omega = 1 - 2^{-\eta}$, the solution to the NSC is as,

$$\vec{\mathbf{x}} = \Big(\omega(1+T), \cdots, \omega(1+T), I_{j+1}, \cdots, I_{k-1}, x_k, \varphi(1+T), \cdots, \varphi(1+T)\Big).$$

- **Theorem**: x_k must satisfy,

$$x_k \leq \min \left\{ \begin{array}{l} I_k \\ \frac{\omega}{\psi-\omega}(L+1)\frac{1}{1-[\psi<\omega]} \\ \psi \min\left\{ \frac{1}{\omega} I_j \frac{1}{1-[j=0]}, \frac{1}{\varphi} I_M, X_{max}+1 \right\} - (L+1) \end{array} \right\},$$

$$x_k \geq \max \left\{ \begin{array}{l} \left(\frac{\psi}{\omega} I_{j+1} - (L+1)\right)(1-[k \leq j+1]) \\ \frac{\varphi}{\psi-\varphi}(L+1) \end{array} \right\}.$$

- Details in the appendix.

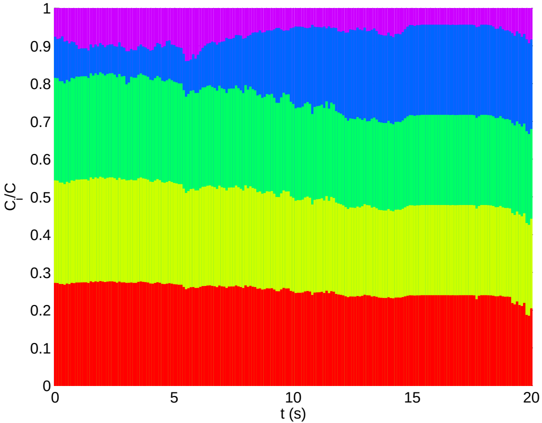
New Single Cell (NSC) - The Solver

- The algorithm has a structure similar to that of the CSC.
- Here, the two indexes of j and k have to iterated.
- Computational cost is of $O(M^3)$, compared to the $O(M^2)$ complexity of the CSC.

$$\tau_{NSC} = \frac{16}{3}M^3 + \frac{55}{3}M^2 - 23M + 6$$

- It takes $2ms$ to solve the NSC in a cell containing 100 stations.

Unfairness of the NSC - Results



Capacity–Share of the Stations in the Solution to the NSC.

The NSC vs. the CSC

Table: Comparison of the CSC with the NSC. The row P denotes the pattern of the solution. Here, the symbols x and X denote that the corresponding station is transmitting at the minimum and the maximum capacities, respectively. Also, b and l denote that x_i is inside the allowed interval or equals l_i, respectively.

Station #		1	2	3	4	5	6	7	8	9	10
g_i ($\times 10^{-12}$)		0.52	0.018	0.016	0.009	0.008	0.008	0.008	0.006	0.006	0.005
	P	b	x	x	x	x	x	x	x	x	x
	p_i	46.527	5.211	5.855	10.439	11.626	11.756	12.617	16.053	16.198	20.916
CSC	C_i	2.361	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	$\tilde{C}_i$	98.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
		$C = 2.402$, $f = 2.356$, $\tilde{f} = 518.2$									
	P	X	l	l	l	l	l	l	l	l	b
	p_i	14.662	16.092	16.189	16.584	28.796	36.313	50.000	13.744	14.535	18.984
NSC	C_i	0.3000	0.2111	0.1863	0.1015	0.0908	0.0898	0.0835	0.0652	0.0646	0.0498
	$\tilde{C}_i$	24.1%	17.0%	15.0%	8.2%	7.3%	7.2%	6.7%	5.2%	5.2%	4.0%
	C	$C = 1.243$, $f = 0.250$, $\tilde{f} = 6.027$									

- More details in the report and the appendix.

New Enhanced Single Cell (N^+SC)

- The notable advantages of the results of the NSC, over those of the CSC, suggest that more direct control on the capacity–shares of the stations may results in further improvements.
- An explicit capacity–share constraint is added to the problem,

$$\tilde{C}_i \leq \frac{1}{\mu}\frac{1}{M}, 0 \leq \mu \leq 1.$$

- The resulting problem is titled the new enhanced single cell (N^+SC).
- Rigorous analysis of the N^+SC is given in the appendix.
- A maximum bound in the computational complexity of the N^+SC is proved to be,

$$\tau_{N^+SC} = \frac{32}{3}M^3 + \frac{128}{3}M^2 - 52M + 20.$$

- The N^+SC utilizes an approximation.
- More details in the appendix.

Approximating C_i

- The following approximation can be used to reduce one in orders of M from the computational complexity of the proposed algorithms.

$$\log_2\left(1+\frac{x}{1-x}\right)\simeq\frac{1}{\ln 2}x\left(1+x\right).$$

  - Leads to C_i being approximated as,

$$C_i\simeq\frac{1}{\ln 2}\frac{x_i}{1+T}\left(1+\frac{x_i}{1+T}\right).$$

- Details and experimental results in the report and the appendix.

Utility Functions: NSC^{f+} and the NSC^{f-}

- Shifting from the maximization of the summation of the capacities to the aggregate satisfaction of the customers.

$$\hat{C}(\vec{\mathbf{p}}) = \sum_{i=1}^{M} f(C_i),$$

- f is a doubly differentiable increasing function.

$$f : \mathbb{R}^+ \cup \{0\} \to \mathbb{R}^+ \cup \{0\},$$

Convex Utility Functions: NSC^{f+}

- Minor modification of the available algorithms produces the solver.
- The importance of this problem is solely theoretical.
    - The migration from the NSC to the NSC^{f+} has no practical benefit.
- Details and experimental results in the report and the appendix.

Concave Utility Functions: NSC^{f-}

- **Theorem**: As opposed to the case of the CSC in which x_is had to be as far from each other as possible, in the NSC^{f-} they have to be as close to each other as possible.
- The NSC^{f-} is intrinsically more fair.
- Experimental results do approve the fairness of the NSC^{f-}.
- Details and experimental results in the report and the appendix.

Multiple–Class Systems: The M^{1}SC and the M^{2}SC

- The bounds are now unique to the stations,

$$\gamma_i \geq \gamma_i^{min}, \forall i,$$

$$C_i \leq C_i^{max}, \forall i,$$

$$\sum_{i=1}^{M} p_i g_i \leq P^{max},$$

$$0 \leq p_i \leq p_i^{max}, \forall i.$$

- The system favors different stations differently.

$$C = \sum_{i=1}^{M} \alpha_i C_i, \alpha_i > 0.$$

Multiple–Class Systems: Substitute Variables

- We propose to substitute,

$$\varphi_i = \frac{\gamma_i}{1+\gamma_i}.$$

- We define,

$$\mathbf{A} = \left[\begin{array}{c} \vec{\mathbf{1}}_{1\times M} \\ \mathbf{1}_{M\times M} + diag\left[\frac{1}{l_1}, \cdots, \frac{1}{l_M}\right] \end{array} \right], \vec{\mathbf{b}} = \left[\begin{array}{c} \frac{X^{max}}{X^{max}+1} \\ \vec{\mathbf{1}}_{M\times 1} \end{array} \right].$$

- The constraints become linear inequalities,

$$\begin{cases} \varphi^{\vec{\mathbf{min}}} \leq \vec{\varphi} \leq \varphi^{\vec{\mathbf{max}}}, \\ \mathbf{A}\vec{\varphi} \leq \vec{\mathbf{b}}. \end{cases}$$

Multiple–Class Systems: The Objective Function

- The objective function can be approximated as a first or a second order function of the set of φ_is,

$$C \simeq \vec{\mathbf{f}}^T \vec{\varphi}$$

$$C \simeq \frac{1}{2}\vec{\varphi}^T \mathbf{H}\vec{\varphi} + \vec{\mathbf{f}}^T \vec{\varphi}.$$

- Here,

$$\vec{\mathbf{f}} = \frac{1}{ln2}\vec{\alpha},$$

$$\mathbf{H} = \frac{2}{ln2} diag\left[\alpha_1, \cdots, \alpha_M\right].$$

- Therefore, linear or quadratic programming can be used for solving the M^1SC and the M^2SC.

Future Directions

- Work on adding more features to the single–cell model.
- Extension of the work to multiple–cell systems.
- Other improvements.

Incorporating ν and α

- ν: Probability of activity of any station at any given time.
  - Value of $\nu = 0.4$ suggested for voice–only systems.
  - A primitive approach suggests the assumption of having only $M\nu$ stations in an M–station system.
- α: Modeling the characteristics between the spreading codes of stations.
  - $\alpha = 1$ and $\alpha = \frac{1}{3}$ for synchronous and asynchronous stations.
- More accurate model for the SIR,

$$\gamma_i = \frac{p_i g_i}{I + \alpha\nu \sum_{j=1, j\neq i}^{M} p_j g_j}.$$

- The developed methods are not directly applicable to this problem.

Incorporating ν and α - Approximation

- Define,

$$\chi = \frac{1}{\alpha\nu}.$$

$$\hat{\gamma}_i = \frac{p_i g_i}{\hat{I} + \sum_{j=1, j\neq i}^{M} p_j g_j},$$

$$\hat{I} = \chi I,$$

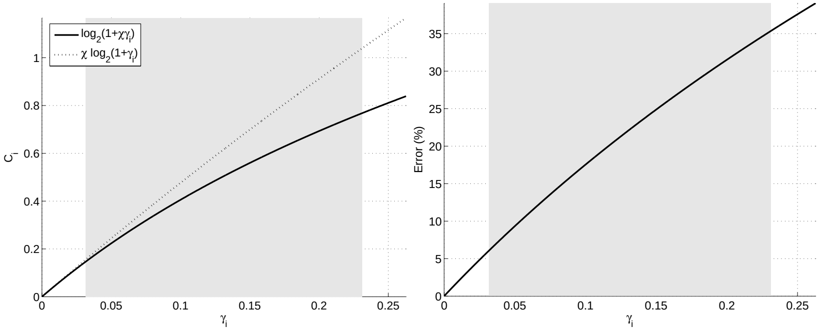
$$\hat{C}_i = \log_2(1 + \hat{\gamma}_i),$$

- It can be shown that,

$$C_i \simeq \chi \hat{C}_i.$$

- Thus, as long as the approximation is within an acceptable range of error, this problem can be approximately solved by the available methods.
-

Validity of the Approximation

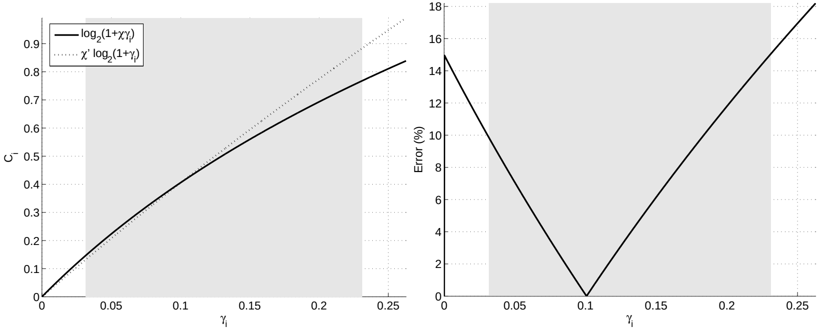


Validity of the approximation for $\chi = 5$.

Better Approximation

- The error of the approximation can be reduced by using,

$$C_i \simeq \chi' \hat{C}_i.$$



Validity of the approximation for $\chi = 5$ and $\chi' = 0.85\chi$.

Symbol–Level Modeling

- For the chip rate of W and the data rate of R,

$$L = \frac{W}{R} > 1.$$

- Symbol–level SIR,

$$\gamma_i = \frac{Lp_ig_i}{I + \sum_{j=1,j\neq i}^{M} p_jg_j}.$$

- Similar to before with a nominal value of $\chi = 100$.

Multiple–Rate Systems

- Define,

$$L_i = \frac{W}{r_i},$$

$$\gamma_i = \frac{L_i p_i g_i}{I + \sum_{j=1, j \neq i}^{M} p_j g_j}.$$

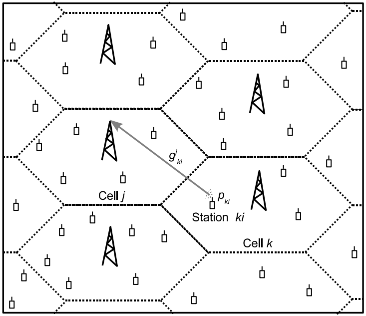
- Define,

$$C_i \simeq \frac{W}{r_i} \hat{C}_i.$$

- The problem can be rewritten as,

$$C \simeq W \sum_{i=1}^{M} \hat{\alpha}_i \hat{C}_i, \hat{\alpha}_i = \frac{\alpha_i}{r_i}.$$

Multiple–Cell Systems: System Model



- K cells, with M_k stations in the k–th cell.
- The i–th station in the k–th cell transmits with the power p_{ki}.
- The path gain from this station to the base station at the j–th cell is denoted by g^j_{ki} ($g_{ki} = g^k_{ki}$).
- Based on *Alpcan* and *Basar* (2004).

Multiple–Cell Systems: System Model

- SIR in the multiple–cell system,

$$\gamma_{ki} = \frac{p_{ki} g_{ki}}{I_k + \sum_{k'=1, k' \neq k}^{K} \sum_{i'=1}^{M_{k'}} p_{k'i'} g_{k'i'}^{k} + \sum_{i'=1, i' \neq i}^{M_k} p_{ki'} g_{ki'}}$$

- A handy notation,

$$\tilde{I}_k = \sum_{k'=1, k' \neq k}^{K} \sum_{i'=1}^{M_{k'}} p_{k'i'} g_{k'i'}^{k}.$$

- Capacity,

$$C_{ki} = \log_2 (1 + \gamma_{ki}),$$

Multiple–Cell Systems: Problem Setup

- Maximize

$$C=\sum_{k=1}^{K}\sum_{i=1}^{M_k}\alpha_{ki}C_{ki},\alpha_{ki}>0,$$

- Given,

$$\gamma_{ki}\geq\gamma_{ki}^{min},\forall i,k,$$

$$C_{ki}\leq C_{ki}^{max},\forall i,k,$$

$$\sum_{i=1}^{M_k}p_{ki}g_{ki}\leq P_k^{max},\forall k,$$

$$0\leq p_{ki}\leq p_{ki}^{max},\forall i,k.$$

Iterative Freeze–Update

- Writing,

$$\gamma_{ki} = \frac{p_{ki}g_{ki}}{\left[I_k + \tilde{I}_k\right] + \sum_{i'=1,i'\neq i}^{M_k} p_{ki'}g_{ki'}}.$$

- The multiple–cell problem can be solved through iterative utilization of single–cell systems.
- Issues of stability and convergence have to be dealt with.

Using Virtual Stations

- δ: The loading factor, also called the intercell interference factor.
- Values of 0.6 and 0.55 suggested in the literature for δ.
- $M\delta$ virtual station model the interference coming outside each cell,

$$\gamma_i = \frac{p_i g_i}{I + (1+\delta)\sum_{j=1, j\neq i}^{M} p_j g_j}.$$

- Here,

$$\chi = \frac{1}{1+\delta} < 1,$$

Reduction to Linear and Quadratic Systems

- The multiple–cell SIR model can be used in the framework applied on the single–cell problem.
- The result will be a single linear or quadratic problem which models the whole system.
- Issues of size, sensitivity to parameters, and computational complexity have to be dealt with.
- Proper substitute variables have to be proposed.

Publications

Conference Papers,

- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, "A More Realistic Approach to Information–Theoretic Sum Capacity of Reverse Link CDMA Systems in a Single Cell", In the IEEE International Conference on Communications (ICC 2007), Glasgow, Scotland.
- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, "Capacity-Share Controlled Information–Theoretic Sum Capacity of Reverse Link Single–Cell CDMA Systems", In the 2007 IEEE 65th Vehicular Technology Conference, (VTC2007 Spring), Dublin, Ireland.
- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, "Information-Theoretic Sum Capacity of Reverse Link CDMA Systems in A Single Cell, An Optimization Perspective", In the 8th Annual Conference for Canadian Queueing Theorists and Practitioners, CanQueue 2006, Banff, Calgary, Canada.
- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, "Closed Form Solution for QoS–Constrained Information–Theoretic Sum Capacity of Reverse Link CDMA Systems", In the 2nd ACM Q2SWinet 2006, Torremolinos, Malaga, Spain.

Journal Papers,

- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, "Approximation Algorithms For Maximizing The Information–Theoretic Sum Capacity of Reverse Link CDMA Systems", AEUE - International Journal of Electronics and Communications, To Appear, 2007.
- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, "Closed Form Solution for Maximizing the Sum Capacity of Reverse–Link CDMA System with Rate Constraints", IEEE Transactions on Wireless Communications, Volume 7, Issue 4, April 2008, Pages:1179–1183.

Thanks for Your Attention, Any Questions?