Cell Design to Maximize Capacity in CDMA Networks

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Outline

- CDMA inter-cell effects
- Capacity region
  - Base station location
  - Pilot-signal power
  - Transmission power of the mobiles
- Maximize network capacity
- Mobility
- Call admission control algorithm
- Network performance

CDMA Capacity Issues

- **Depends on inter-cell interference and intra-cell interference**
- **Complete frequency reuse**
- **Soft Handoff**
- **Power Control**
- **Sectorization**
- **Voice activity detection**
- **Graceful degradation**

Relative Average Inter-Cell Interference

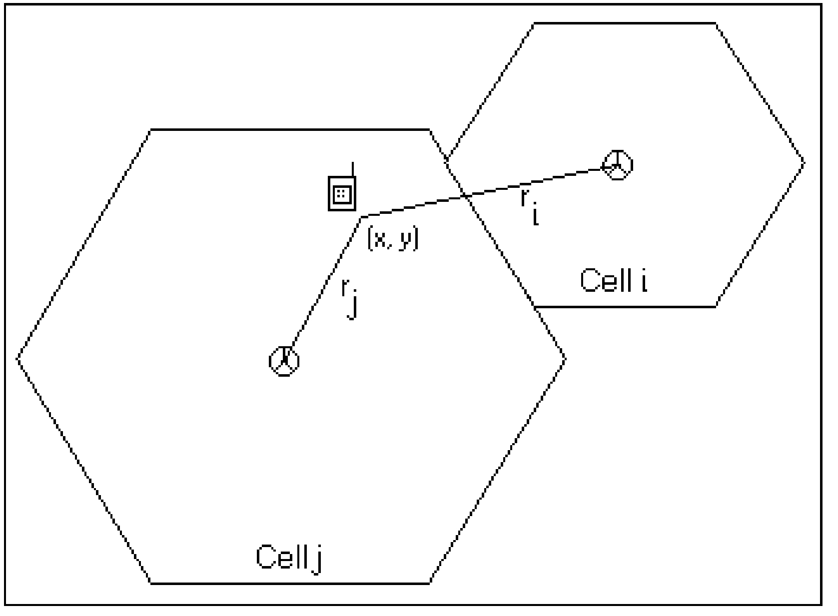
$$I_{ji} = \mathrm{E}\left[\iint_{C_j} \frac{r_j^m(x,y)10^{\zeta_j/10}}{r_i^m(x,y)/\chi_i^2} \omega_j \, dA(x,y) \right]$$

m is the path loss exponent.

ζ_i is the decibel attenuation due to shadowing, and has zero mean and standard deviation σ_s.

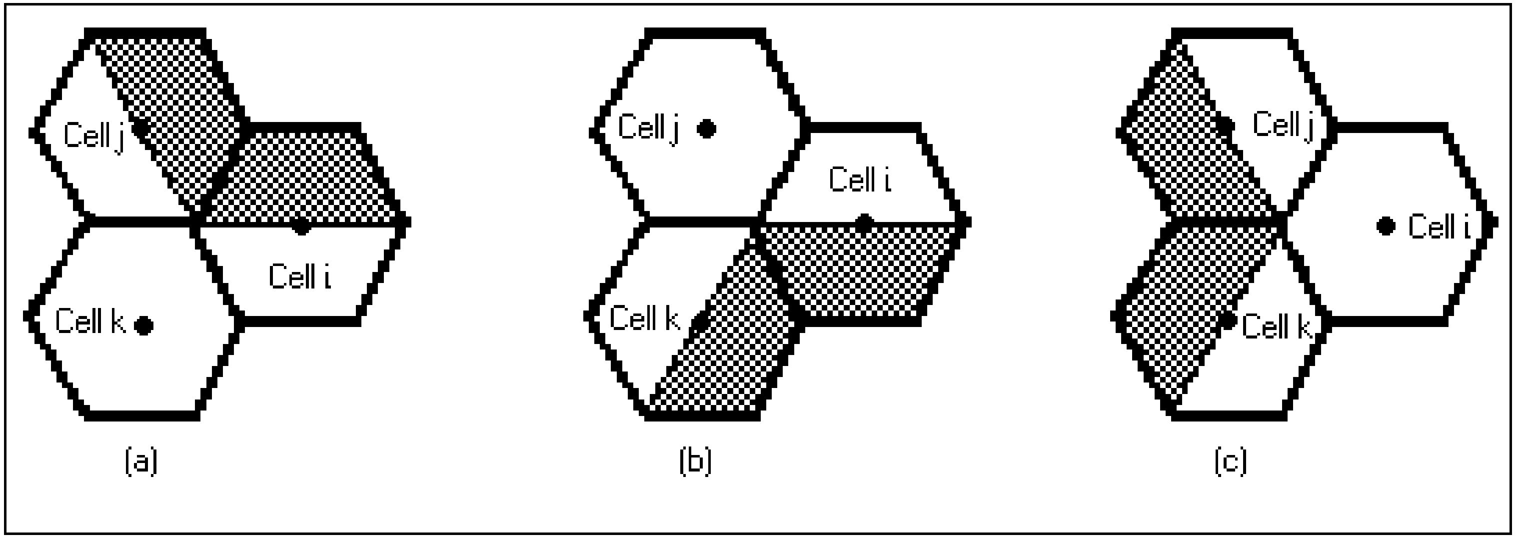
$$\mathrm{E}\left[\chi_i^2 | \zeta_i\right] = 10^{-\zeta_i/10}$$

$$\omega_j = \frac{n_j}{\mathrm{Area}(C_j)}$$



Soft Handoff

- **User is permitted to be in soft handoff to its two nearest cells.**



Soft Handoff

$$I_{ji} = \iint_{\text{region(a)}} \frac{r_j^m}{r_i^m} \mathrm{E}\left[10^{\zeta_j/10} \chi_i^2 \middle| r_j^m 10^{\zeta_j/10} < r_i^m 10^{\zeta_i/10}\right] \omega dA(x,y)$$

$$I_{ki} = \iint_{\text{region(b)}} \frac{r_k^m}{r_i^m} \mathrm{E}\left[10^{\zeta_k/10} \chi_i^2 \middle| r_k^m 10^{\zeta_k/10} < r_i^m 10^{\zeta_i/10}\right] \omega dA(x,y)$$

$$I_{ji} = \iint_{\text{region(c)}} \frac{r_j^m}{r_i^m} \mathrm{E}\left[10^{\zeta_j/10} \chi_i^2 \middle| r_j^m 10^{\zeta_j/10} < r_k^m 10^{\zeta_k/10}\right] \omega dA(x,y)$$

$$I_{ki} = \iint_{\text{region(c)}} \frac{r_k^m}{r_i^m} \mathrm{E}\left[10^{\zeta_k/10} \chi_i^2 \middle| r_k^m 10^{\zeta_k/10} < r_j^m 10^{\zeta_j/10}\right] \omega dA(x,y)$$

Inter-Cell Interference Factor

κ_{ji} per user inter-cell interference factor from cell j to cell i.

n_j users in cell j produce a relative average interference in cell i equal to $n_j \kappa_{ji}$.

Capacity Region

$$\frac{E_b}{\alpha(n_i - 1)E_b R/W + \alpha \sum_{j=1}^{M} n_j \kappa_{ji} E_b R/W + N_0} \geq \left(\frac{E_b}{I_0}\right)_{\text{req}}$$

$$\text{for} \quad i = 1, \ldots, M.$$

$$n_i + \sum_{j=1}^{M} n_j \kappa_{ji} \leq \frac{W/R}{\alpha} \left(\frac{1}{\left(\frac{E_b}{I_0}\right)_{\text{req}}} - \frac{1}{\frac{E_b}{N_0}} \right) + 1 \stackrel{\Delta}{=} c_{\text{eff}}$$

$$\text{for} \quad i = 1, \ldots, M.$$

Network Capacity

$$\max_{(n_1,\ldots,n_M)} \quad \sum_{i=1}^{M} n_i, \text{ (network capacity)}$$

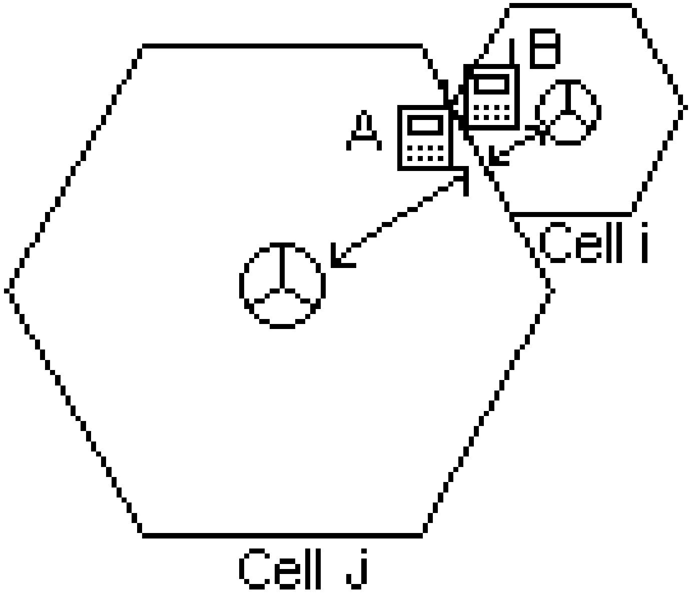
$$\text{subject to} \quad n_i + \sum_{j=1}^{M} n_j \kappa_{ji} - c_{eff} \le 0,$$

$$\text{for} \quad i = 1,\ldots,M.$$

- **Transmission power of mobiles**
- **Pilot-signal power**
- **Base station location**

Power Compensation Factor

- **Fine tune the nominal transmission power of the mobiles**
- **PCF defined for each cell**
- **PCF is a design tool to maximize the capacity of the entire network**



Power Compensation Factor (PCF)

- **Interference is linear in PCF**

$$I_{ji} = \mathrm{E}\left[\iint_{C_j} \frac{\beta_j r_j^m 10^{\zeta_j/10}}{r_i^m/\chi_i^2} \omega_j dA \right]$$

$$n_i + \sum_{j=1}^{M} n_j \frac{\beta_j \kappa_{ji}}{\beta_i} \le c_{eff}(\beta_i) \text{ for } i = 1,\ldots,M.$$

- **Find the sensitivity of the network capacity w.r.t. the PCF**

Sensitivity w.r.t. pilot-signal power

- **Increasing the pilot-signal power of one cell:**
  - **Increases intra-cell interference and decreases inter-cell interference in that cell**
  - **Opposite effect takes place in adjacent cells**

Sensitivity w.r.t. Location

- **Moving a cell away from neighbor A and closer to neighbor B:**
  - **Inter-cell interference from neighbor A increases**
  - **Inter-cell interference from neighbor B decreases**

Optimization using PCF

$$\max_{\underline{\beta}} \quad \sum_{i=1}^{M} n_i, \quad \text{(network capacity)}$$

subject to

$$1 \le \underline{\beta} \le \underline{\beta}^{\max},$$

$$n_i + \sum_{j=1}^{M} n_j \frac{\beta_j \kappa_{ji}}{\beta_i} - c_{eff}(\beta_i) \le 0,$$

$$\text{for} \quad i = 1, \ldots, M.$$

Optimization using Location

$$\max_{\underline{L}} \quad \sum_{i=1}^{M} n_i, \quad \text{(network capacity)}$$

$$\text{subject to} \quad n_i + \sum_{j=1}^{M} n_j \frac{\beta_j \kappa_{ji}(C_j, L_i)}{\beta_i} - c_{eff}^{(i)} \le 0,$$

$$\text{for} \quad i = 1, \ldots, M.$$

Optimization using Pilot-signal Power

$$\max_{\underline{T}} \quad \sum_{i=1}^{M} n_i, \quad \text{(network capacity)}$$

$$\text{subject to} \quad n_i + \sum_{j=1}^{M} n_j \frac{\beta_j \kappa_{ji}(C_j, L_i)}{\beta_i} - c_{eff}^{(i)} \leq 0,$$

$$\text{for } i = 1, \ldots, M.$$

Combined Optimization

$$\max_{\underline{\beta},\underline{L},\underline{T}} \quad \sum_{i=1}^{M} n_i, \quad \text{(network capacity)}$$

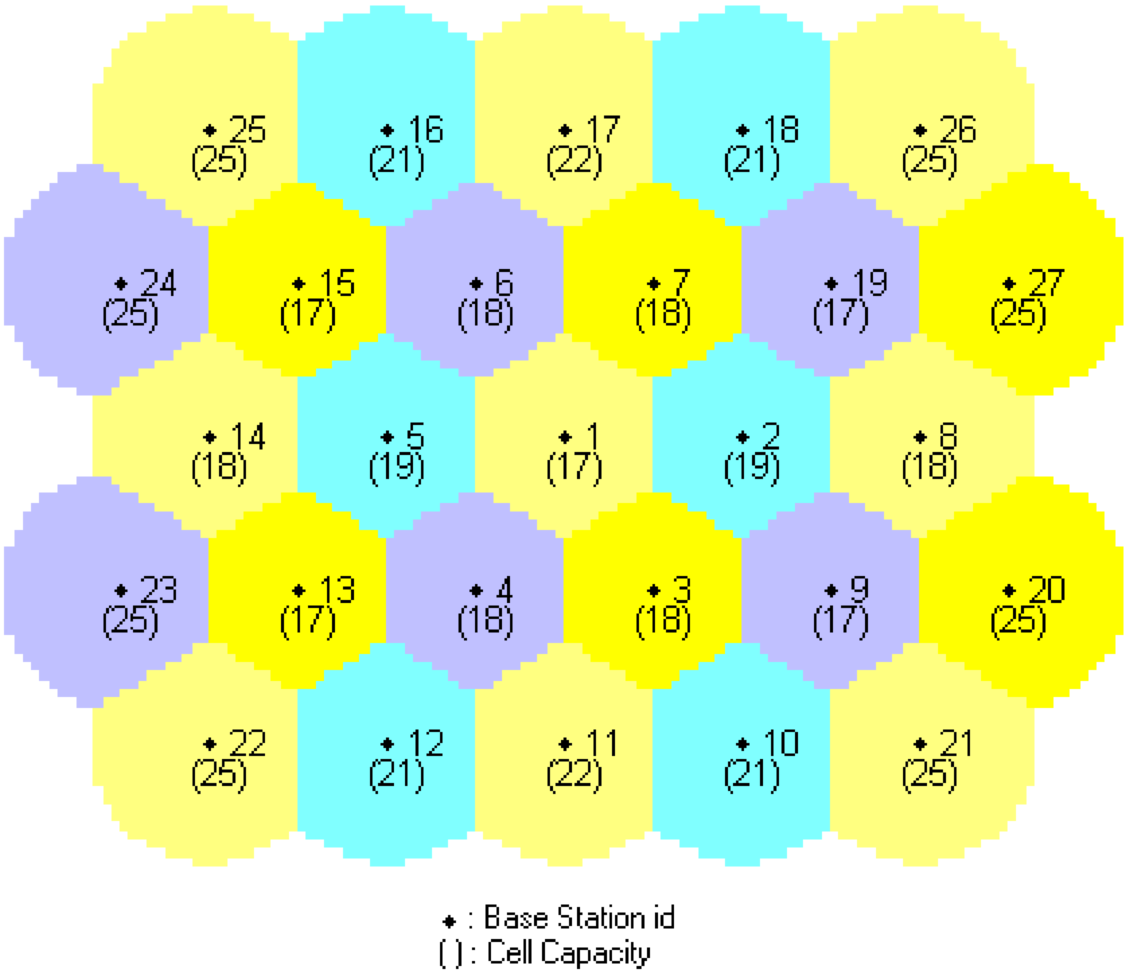
$$\text{subject to} \quad 1 \leq \underline{\beta} \leq \underline{\beta}^{\max},$$

$$n_i + \sum_{j=1}^{M} n_j \frac{\beta_j \kappa_{ji}(C_j, L_i)}{\beta_i} - c_{eff}(\beta_i) \leq 0,$$

$$\text{for} \quad i = 1,\ldots,M.$$

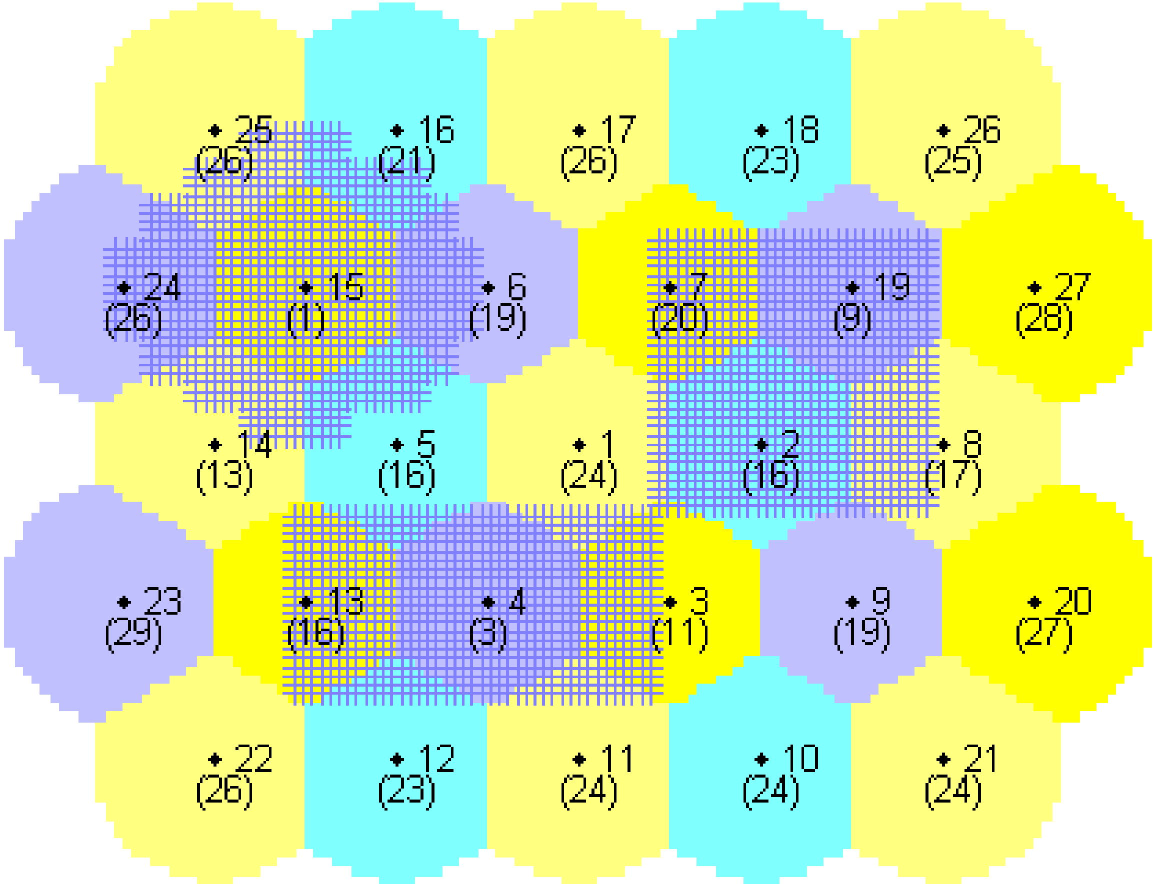
Twenty-seven Cell CDMA Network

- **Uniform user distribution profile.**
- **Network capacity equals 559 simultaneous users.**
- **Uniform placement is optimal for uniform user distribution.**



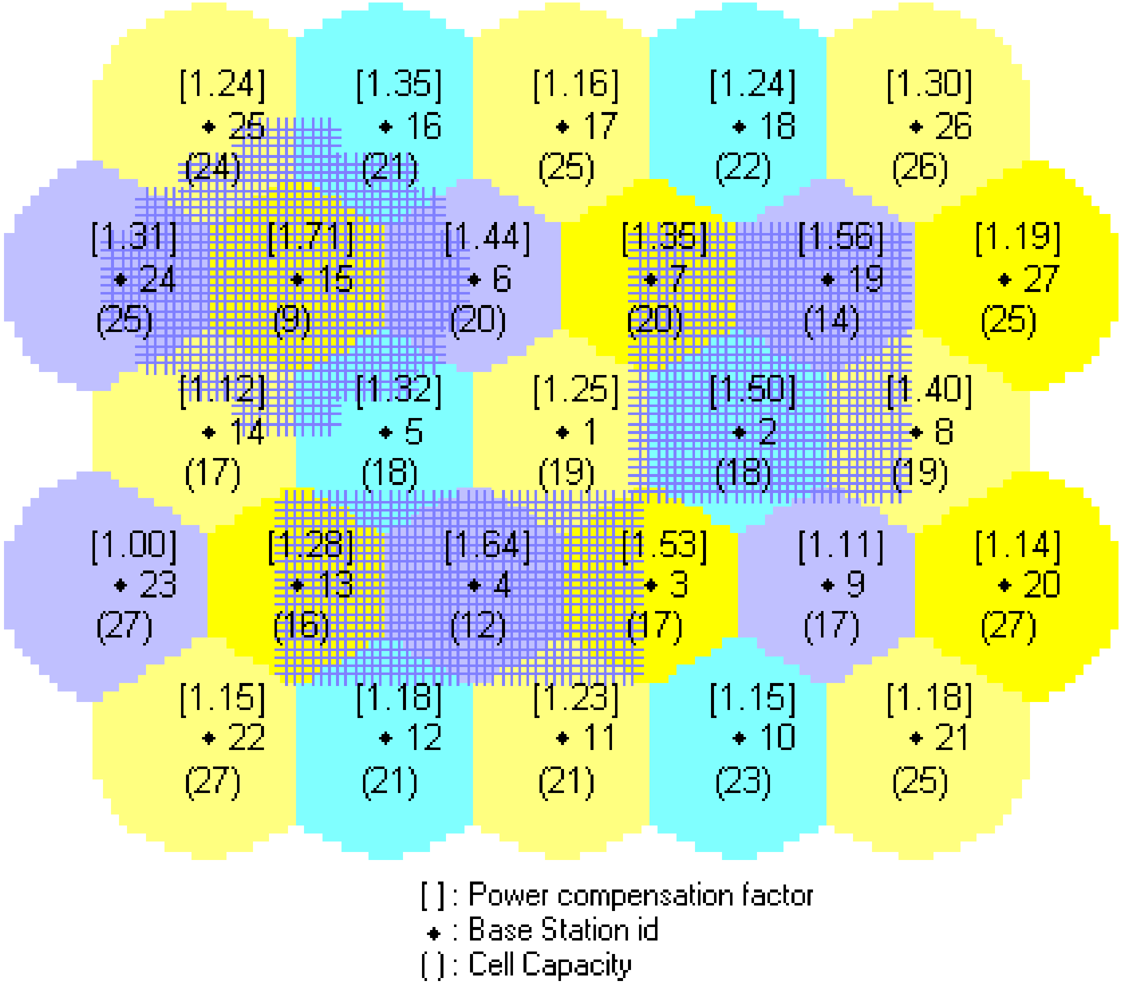
Three Hot Spots

- **All three hot spots have a relative user density of 5 per grid point.**
- **Network capacity decreases to 536.**
- **Capacity in cells 4, 15, and 19, decreases from 18 to 3, 17 to 1, and 17 to 9.**



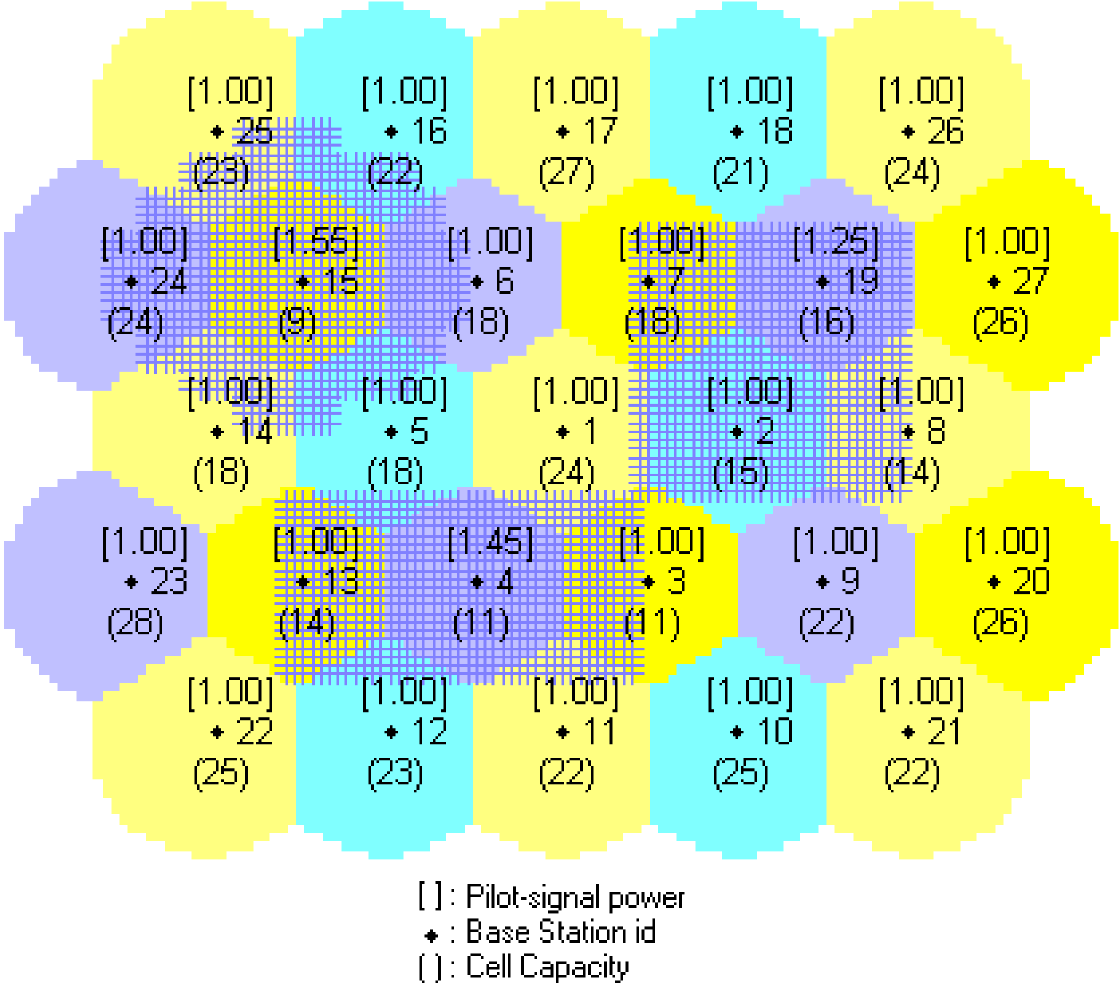
Optimization using PCF

- Network capacity increases to 555.
- Capacity in cells 4, 15, and 19, increases from 3 to 12, 1 to 9, and 9 to 14.
- Smallest cell-capacity is 9.



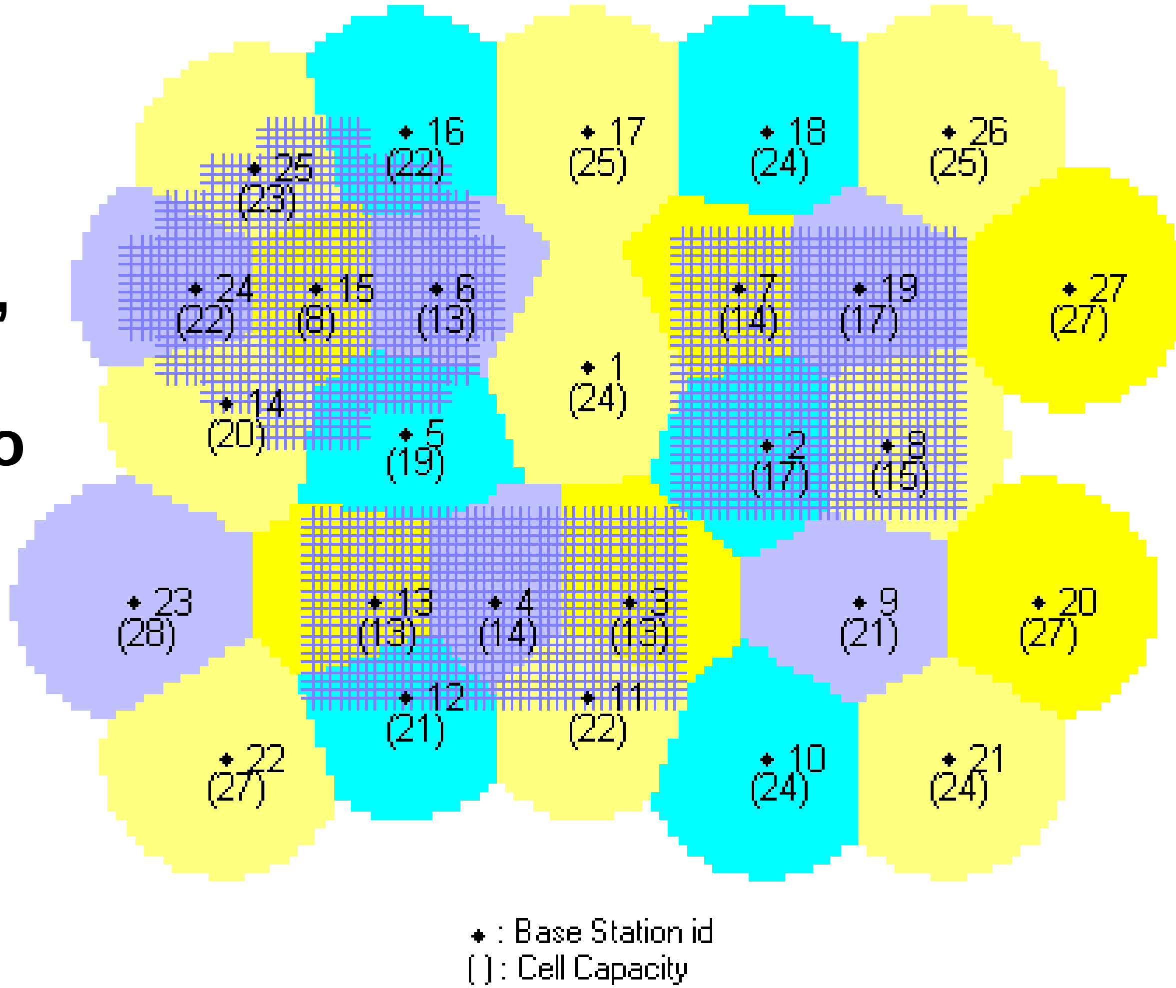
Optimization using Pilot-signal Power

- **Network capacity increases to 546.**
- **Capacity in cells 4, 15, and 19, increases from 3 to 11, 1 to 9, and 9 to 16.**
- **Smallest cell-capacity is 9.**



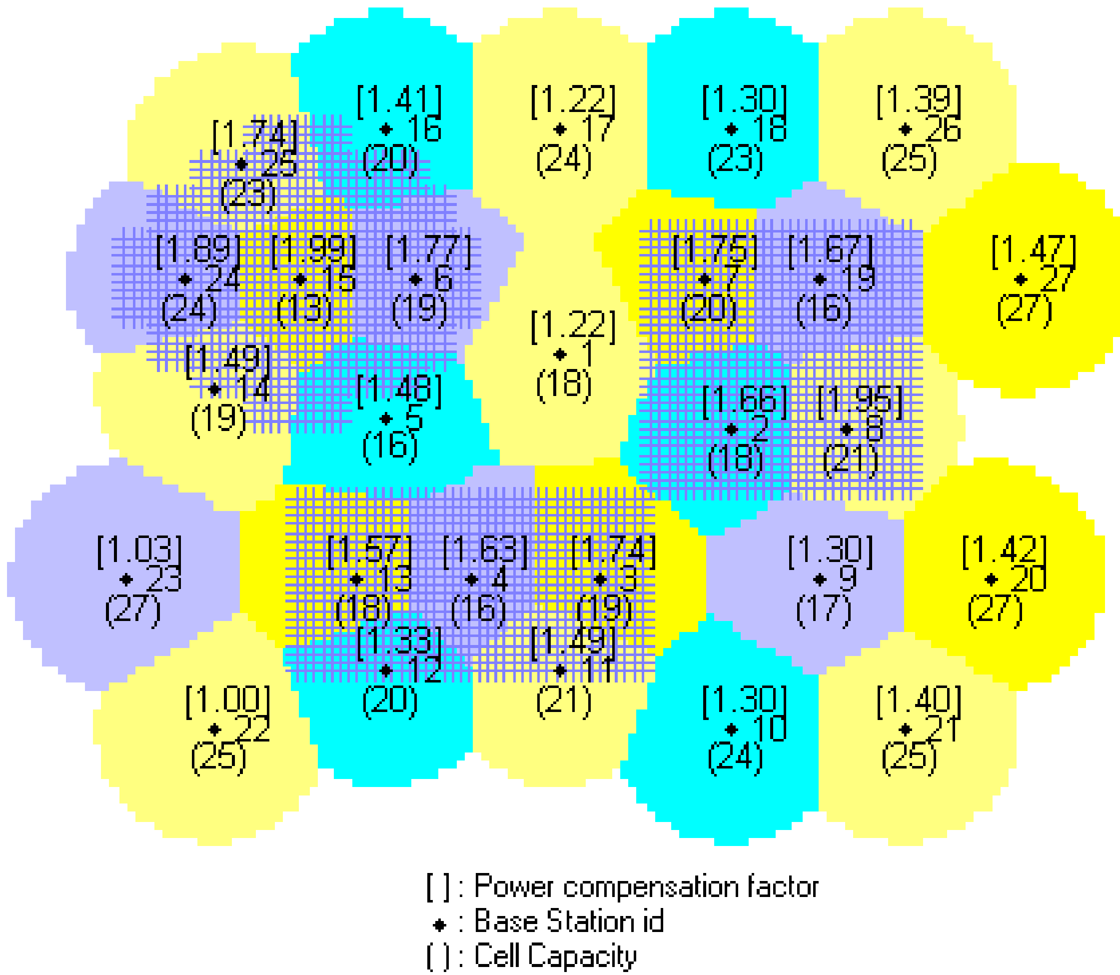
Optimization using Location

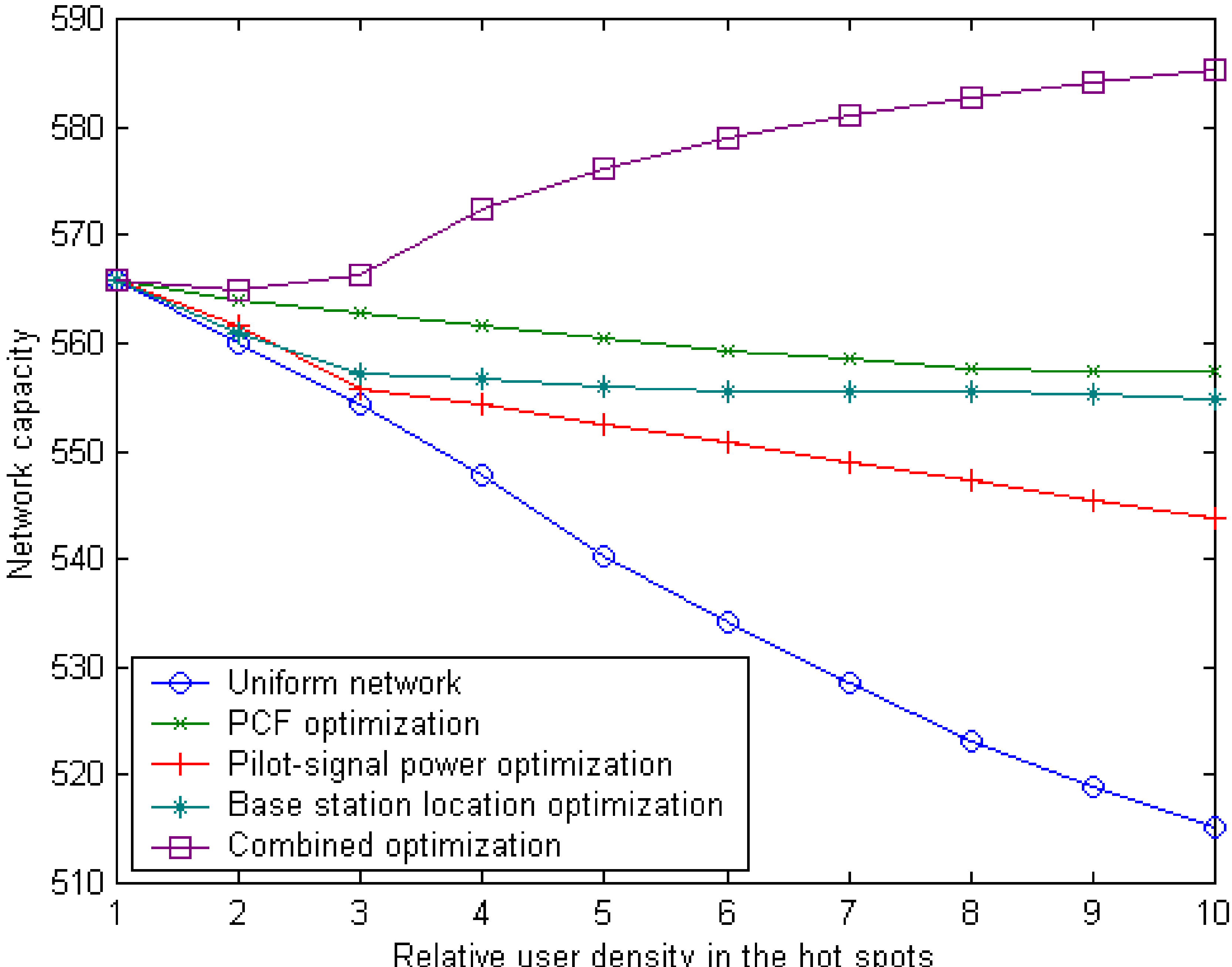
- **Network capacity increases to 549.**
- **Capacity in cells 4, 15, and 19, increases from 3 to 14, 1 to 8, and 9 to 17.**
- **Smallest cell-capacity is 8.**



Combined Optimization

- Network capacity increases to 565.
- Capacity in cells 4, 15, and 19, increases from 3 to 16, 1 to 13, and 9 to 16.
- Smallest cell-capacity is 13.





Network capacity
590
580
570
560
550
540
530
520
510
1
2
3
4
5
6
7
8
9
10
Relative user density in the hot spots
Uniform network
PCF optimization
Pilot-signal power optimization
Base station location optimization
Combined optimization

Combined Optimization (m.c.)

$$\max_{\underline{\beta},\underline{L},\underline{T}} \quad \sum_{i=1}^{M} n_i, \quad \text{(network capacity)}$$

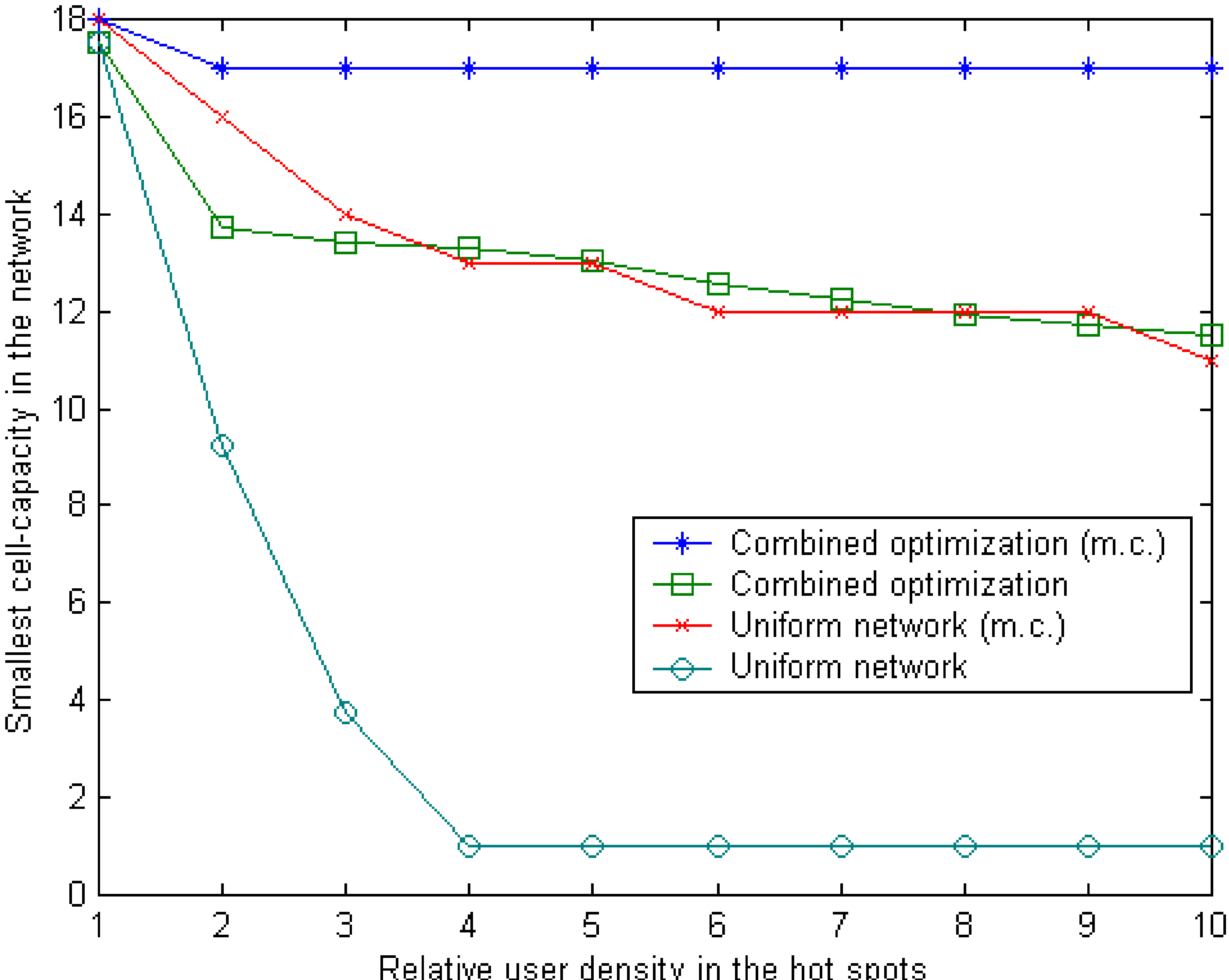
subject to

$$1 \le \underline{\beta} \le \underline{\beta}^{\max},$$

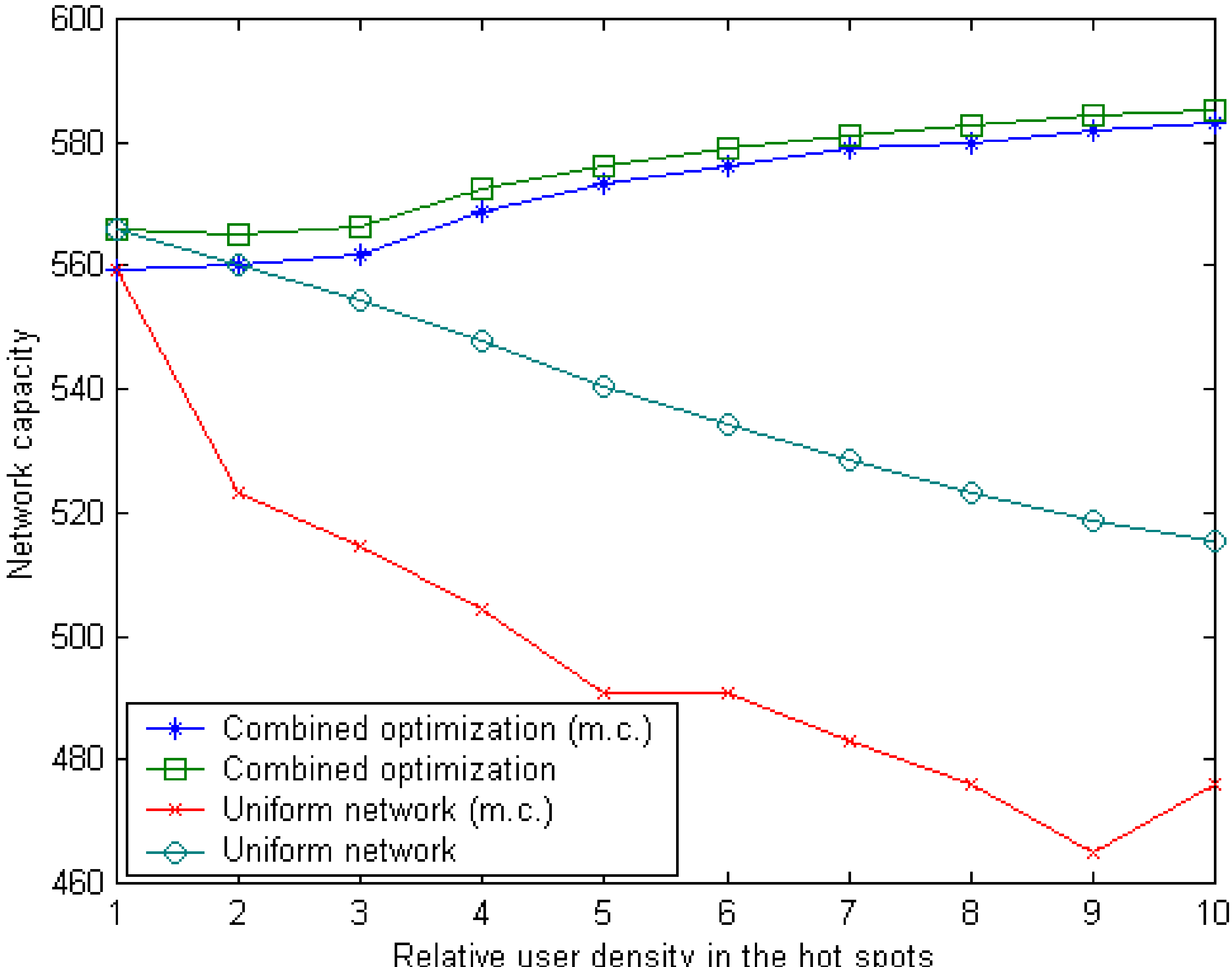
$$n_i + \sum_{j=1}^{M} n_j \frac{\beta_j \kappa_{ji}(C_j, L_i)}{\beta_i} - c_{eff}(\beta_i) \le 0,$$

$$n_i \ge \lfloor n_{\min} \rfloor,$$

$$\text{for} \quad i = 1, \ldots, M.$$



Smallest cell-capacity in the network
Relative user density in the hot spots
0
2
4
6
8
10
12
14
16
18
1
2
3
4
5
6
7
8
9
10
Combined optimization (m.c.)
Combined optimization
Uniform network (m.c.)
Uniform network



600
580
560
540
520
500
480
460
1
2
3
4
5
6
7
8
9
10
Network capacity
Relative user density in the hot spots
Combined optimization (m.c.)
Combined optimization
Uniform network (m.c.)
Uniform network

Call Admission Control

- **Fix cell design parameters**
- **Design a call admission control algorithm**
  - **Guarantees quality of service requirements**
  - **“Good” blocking probability**

Our Model

- **New call arrival process to cell *i* is Poisson.**
- **Total offered traffic to cell *i* is:**

$$\rho_i = \lambda_i + \sum_{j \in A_i} v_{ji}$$

where λ_i is the rate of the Poisson Process,

v_{ji} is the handoff rate from cell j to cell i,

A_i is the set of cells adjacent to cell i.

Handoff Rate

$$v_{ji} = \lambda_j (1 - B_j) q_{ji} + (1 - B_j) q_{ji} \sum_{x \in A_j} v_{xj}$$

$$= (1 - B_j) q_{ji} \rho_j$$

where B_j is the Blocking probabilit y for cell j,

q_{ji} is the probabilit y that a call in progress in cell j, after completing its dwell time, goes to cell i.

Blocking Probability

$$B_i = B(A_i, N_i) = \frac{A_i^{N_i} / N_i!}{\sum_{k=0}^{N_i} A_i^k / k!}, \text{ where } A_i = \frac{\rho_i}{\mu_i},$$

$$N_i + \sum_{j=1}^{M} N_j \kappa_{ji} \le c_{\text{eff}} \quad \text{for } i = 1, \ldots, M.$$

Fixed Point

- Given valu es of λ_i for $i = 1, \ldots, M$
- Assume initial values for v_{ij} for $i, j = 1, \ldots, M$
- Calculate ρ_i for $i = 1, \ldots, M$
- Calculate B_i for $i = 1, \ldots, M$
- Calculate the new values of v_{ij} for $i, j = 1, \ldots, M$

  and repeat

Net Revenue *H*

- **Revenue generated by accepting a new call**
- **Cost of a forced termination due to handoff failure**

$$H = \sum_{i=1}^{M} \left\{ w_i \lambda_i \left(1 - B_i\right) - c_i \left(\rho_i - \lambda_i\right) B_i \right\}$$

- **Finding the derivative of *H* w.r.t. the arrival rate and w.r.t. *N* is difficult.**

Maximization of Net Revenue

$$\max_{(N_1,\ldots,N_M)} \quad \sum_{j=1}^{M} \left\{ w_j \lambda_j \left(1 - B_j\right) - c_j \left(\rho_j - \lambda_j\right) B_j \right\}$$

subject to

$$B(A_i, N_i) \le \eta,$$

$$N_i + \sum N_j \kappa_{ji} \le c_{eff},$$

$$\text{for} \quad i = 1, \ldots, M.$$

3 Mobility Cases

No mobility

q_{ii}= 0.3 and q_i= 0.7

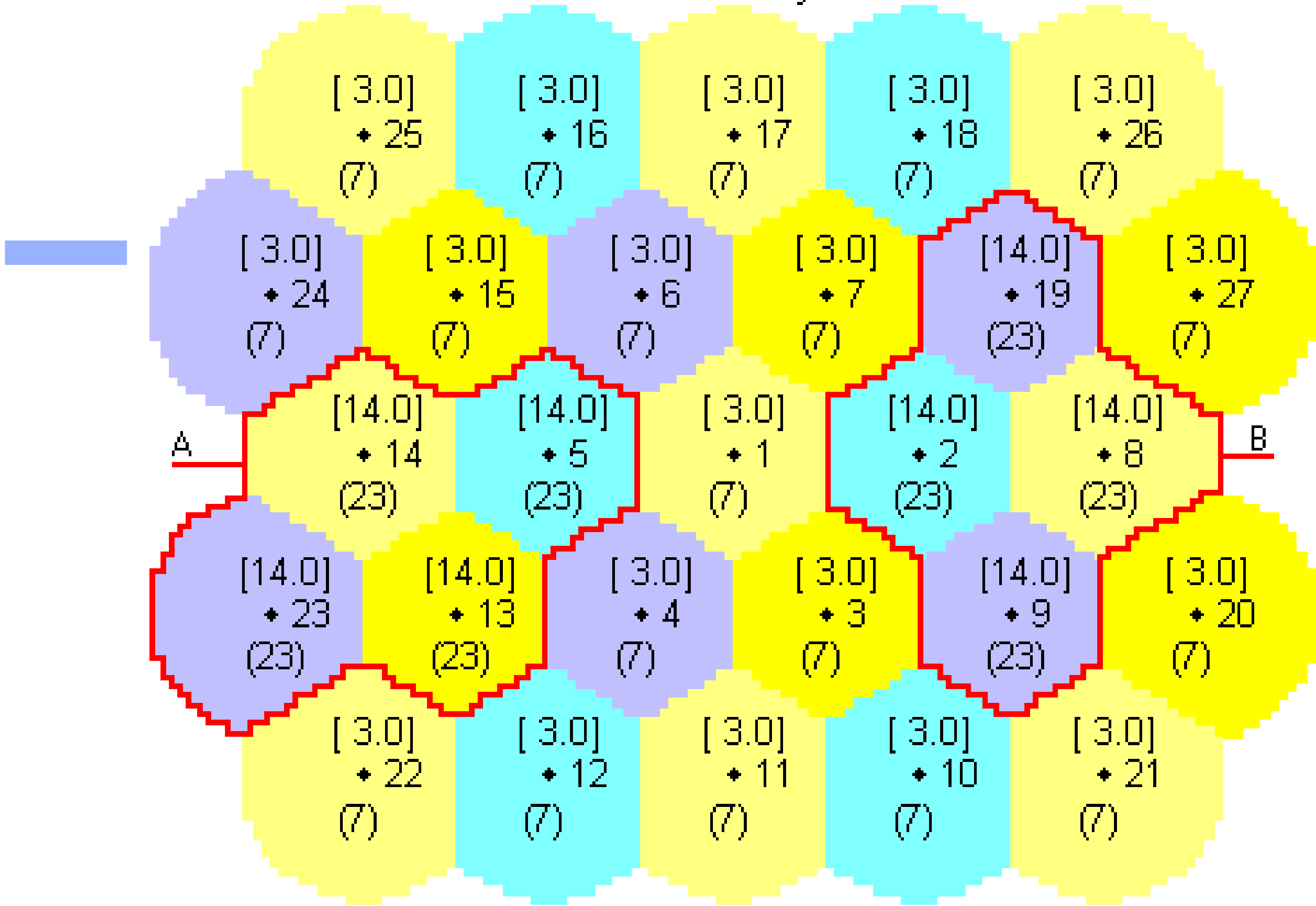
Low Mobility

$\|\|A_i\|\|$	q_{ij}	q_{ii}	q_i
3	0.020	0.24	0.7
4	0.015	0.24	0.7
5	0.012	0.24	0.7
6	0.010	0.24	0.7

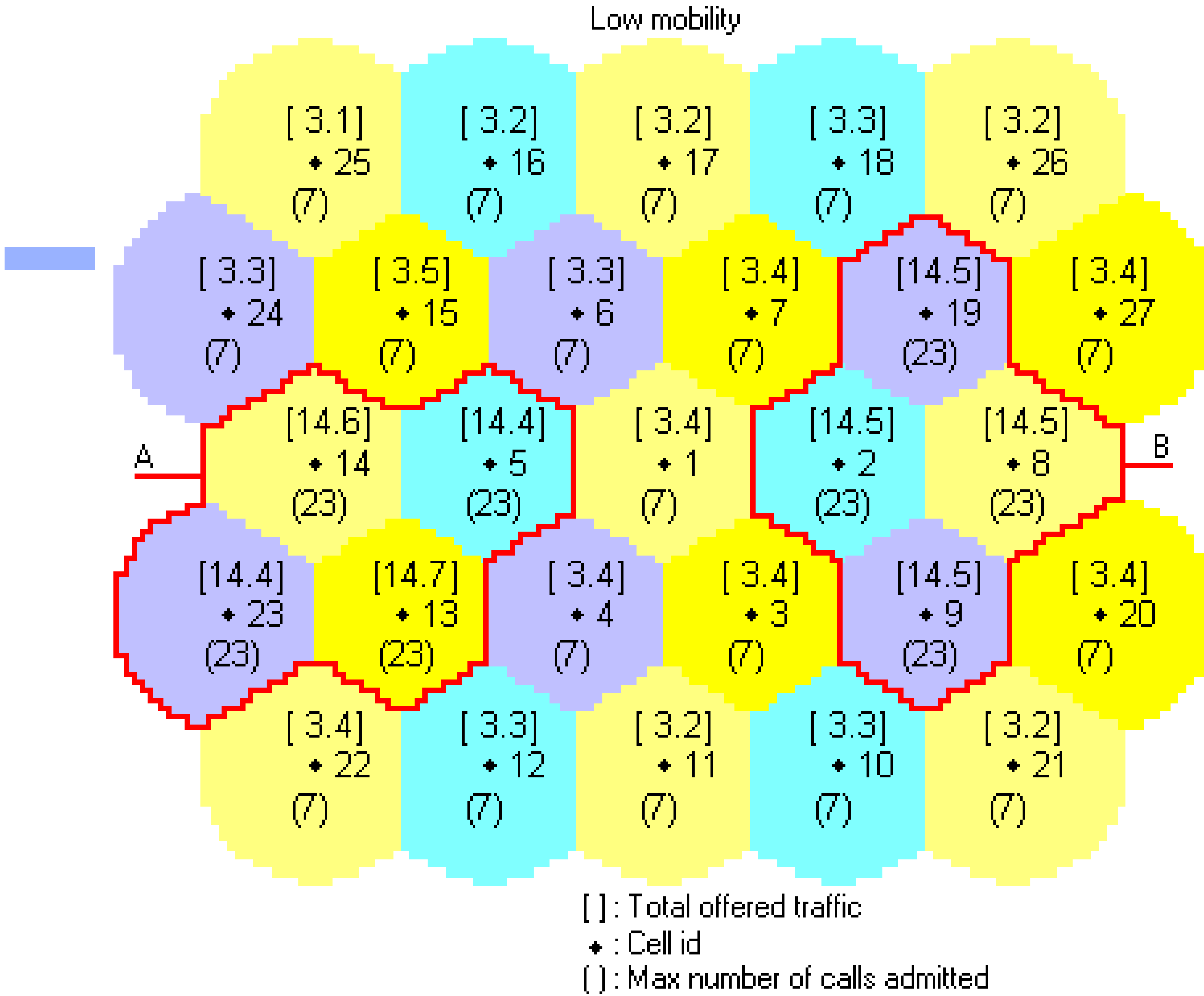
High Mobility

$\|\|A_i\|\|$	q_{ij}	q_{ii}	q_i
3	0.100	0.0	0.7
4	0.075	0.0	0.7
5	0.060	0.0	0.7
6	0.050	0.0	0.7

No mobility



[ ] : Total offered traffic
◆ : Cell id
( ) : Max number of calls admitted


Low mobility
[3.1] 25 (7)
[3.2] 16 (7)
[3.2] 17 (7)
[3.3] 18 (7)
[3.2] 26 (7)
[3.3] 24 (7)
[3.5] 15 (7)
[3.3] 6 (7)
[3.4] 7 (7)
[14.5] 19 (23)
[3.4] 27 (7)
A
[14.6] 14 (23)
[14.4] 5 (23)
[3.4] 1 (7)
[14.5] 2 (23)
[14.5] 8 (23)
B
[14.4] 23 (23)
[14.7] 13 (23)
[3.4] 4 (7)
[3.4] 3 (7)
[14.5] 9 (23)
[3.4] 20 (7)
[3.4] 22 (7)
[3.3] 12 (7)
[3.2] 11 (7)
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[3.2] 21 (7)
[ ] : Total offered traffic
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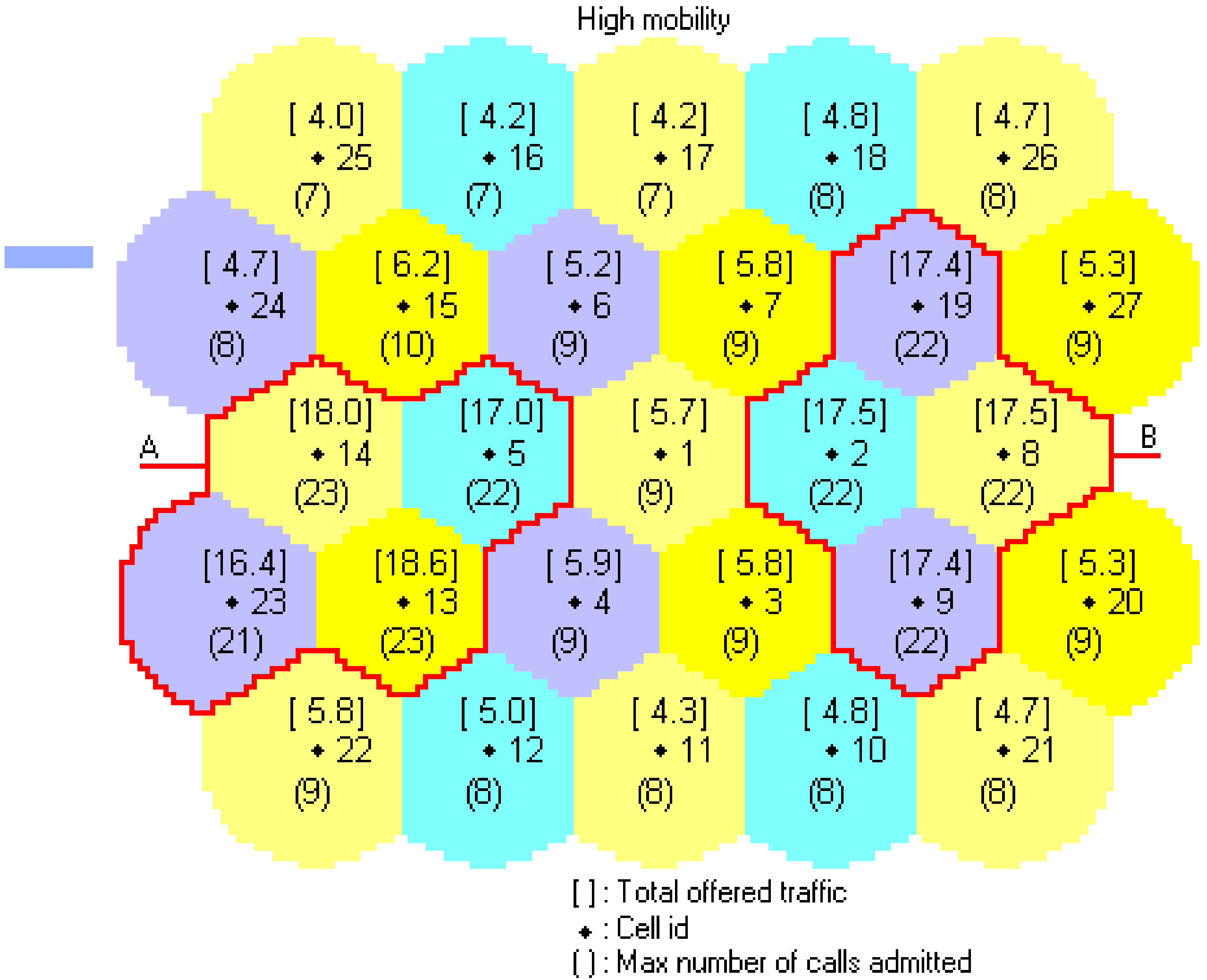
High mobility
[4.0] 25 (7)
[4.2] 16 (7)
[4.2] 17 (7)
[4.8] 18 (8)
[4.7] 26 (8)
[4.7] 24 (8)
[6.2] 15 (10)
[5.2] 6 (9)
[5.8] 7 (9)
[17.4] 19 (22)
[5.3] 27 (9)
A
[18.0] 14 (23)
[17.0] 5 (22)
[5.7] 1 (9)
[17.5] 2 (22)
[17.5] 8 (22)
B
[16.4] 23 (21)
[18.6] 13 (23)
[5.9] 4 (9)
[5.8] 3 (9)
[17.4] 9 (22)
[5.3] 20 (9)
[5.8] 22 (9)
[5.0] 12 (8)
[4.3] 11 (8)
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[4.7] 21 (8)
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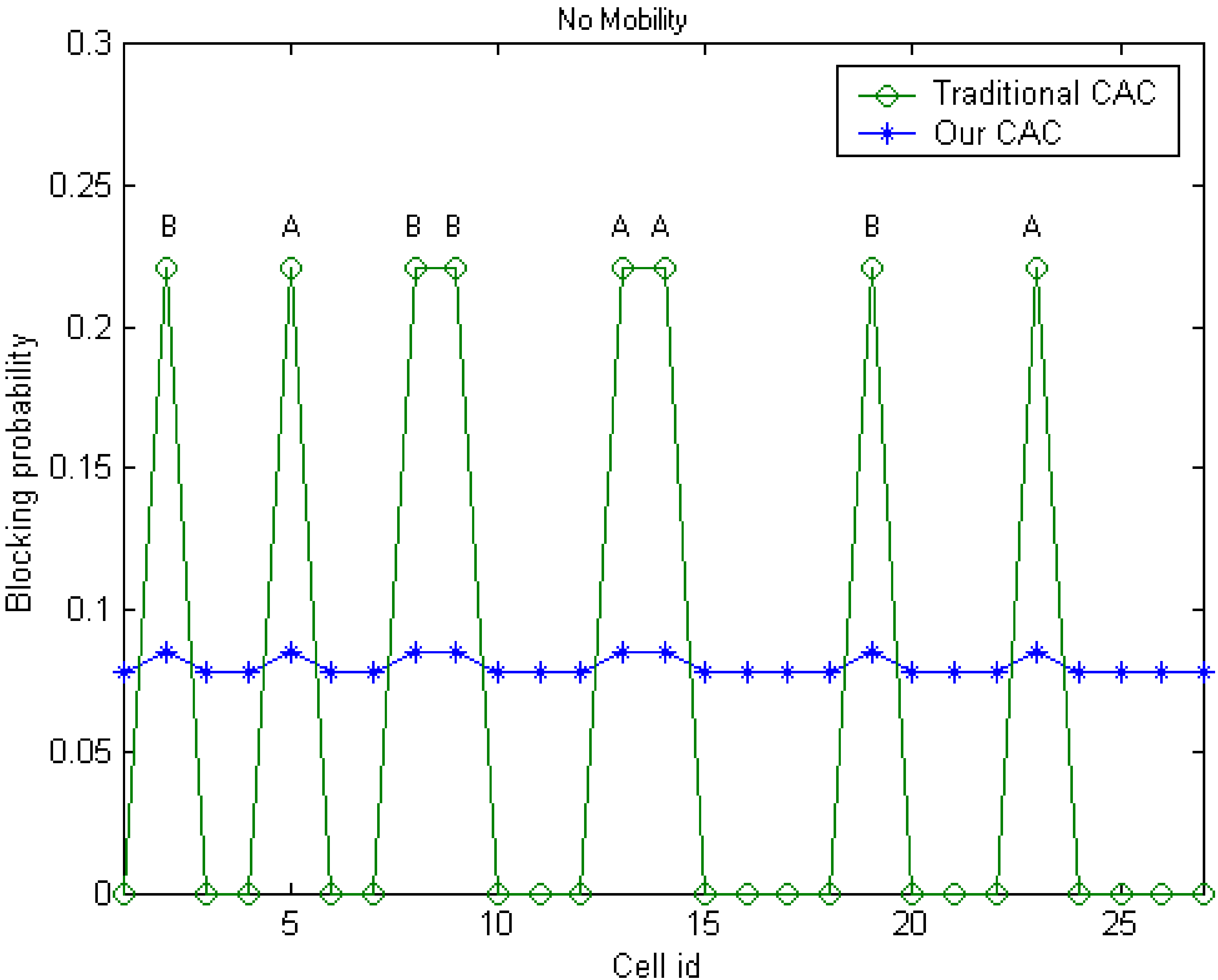
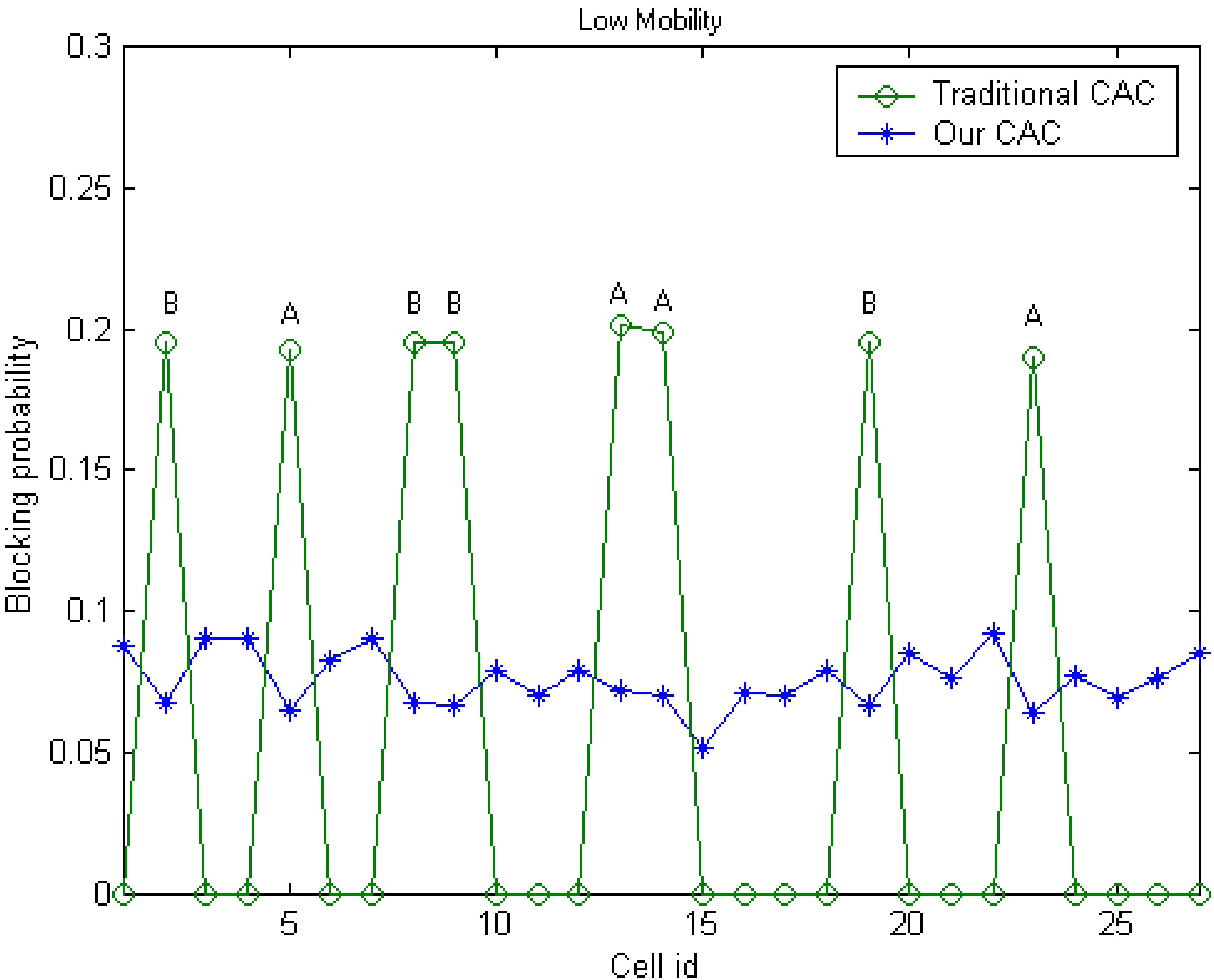
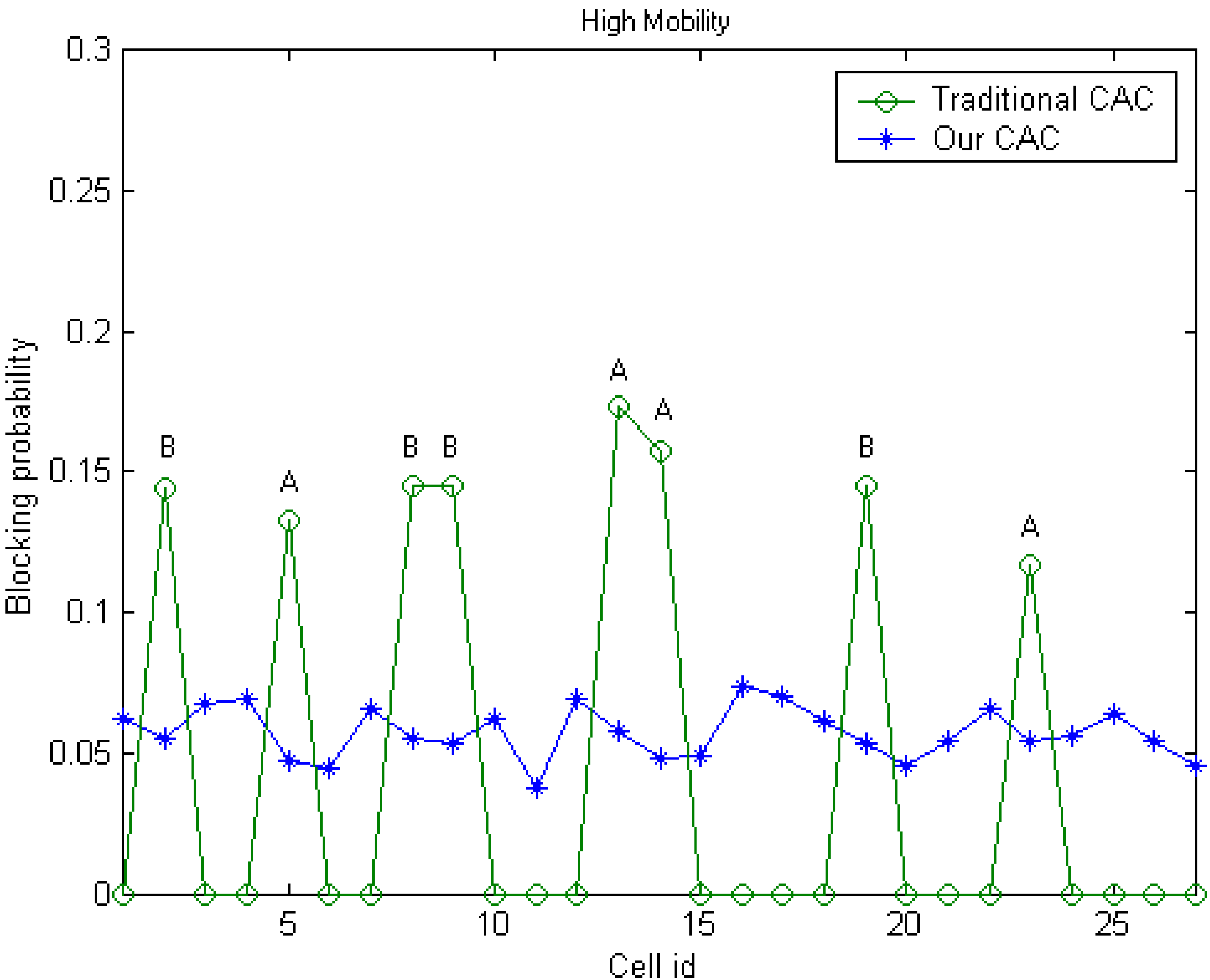


No Mobility
Traditional CAC
Our CAC
B
A
B
B
A
A
B
A
0.3
0.25
0.2
0.15
0.1
0.05
0
Blocking probability
5
10
15
20
25
Cell id



Low Mobility
Traditional CAC
Our CAC
B
A
B
B
A
A
B
A
Blocking probability
0
0.05
0.1
0.15
0.2
0.25
0.3
5
10
15
20
25
Cell id


High Mobility
Traditional CAC
Our CAC
Blocking probability
Cell id
0
0.05
0.1
0.15
0.2
0.25
0.3
5
10
15
20
25
A
B

Maximization of Throughput

$$\max_{(\lambda_1,\ldots,\lambda_M),(N_1,\ldots,N_M)} \quad \sum_{j=1}^{M} \left\{ w_j \lambda_j \left(1 - B_j\right) - c_j \left(\rho_j - \lambda_j\right) B_j \right\}$$

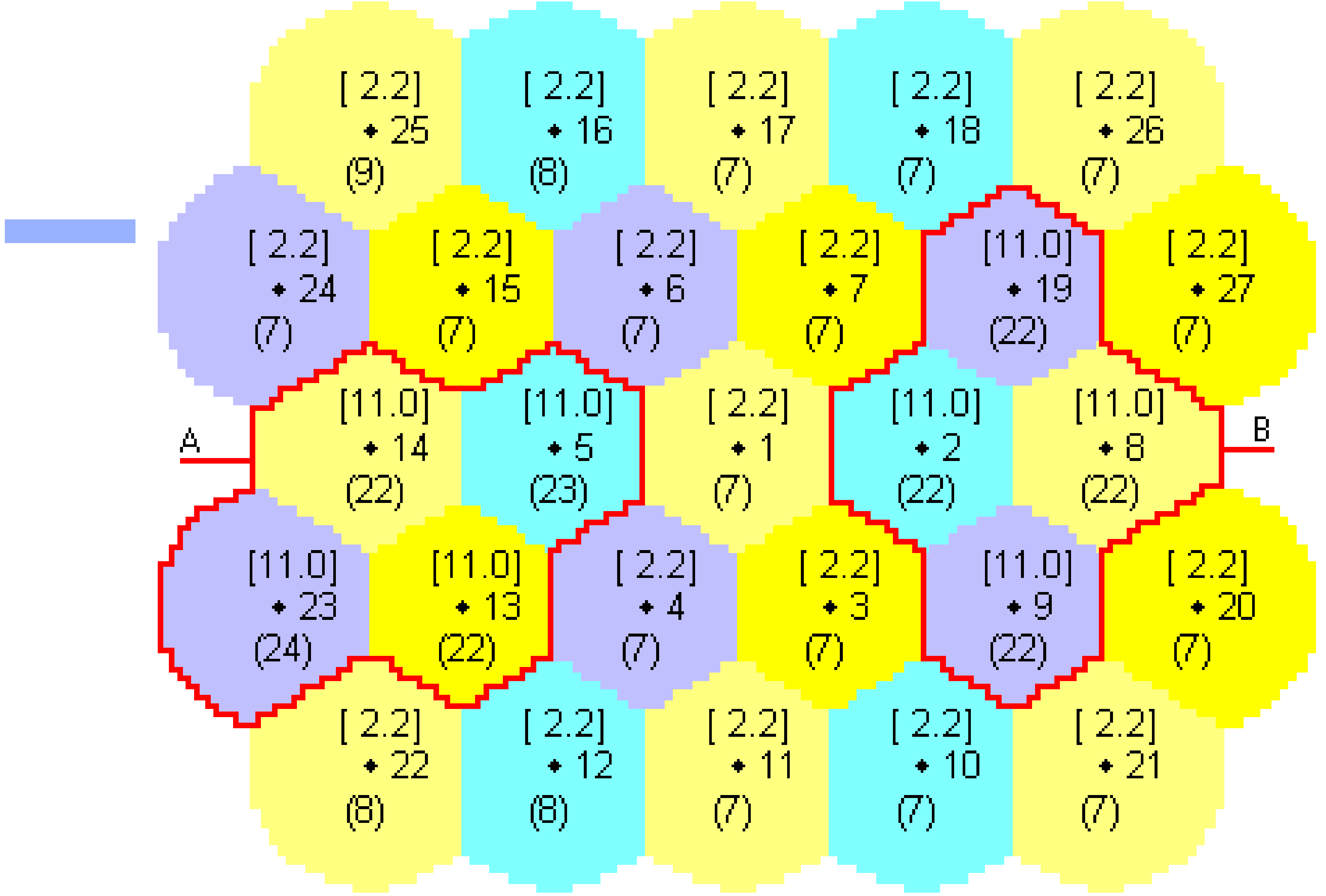
subject to

$$B(A_i, N_i) \le \eta,$$

$$N_i + \sum N_j \kappa_{ji} \le c_{eff},$$

$$\text{for} \quad i = 1, \ldots, M.$$

No mobility



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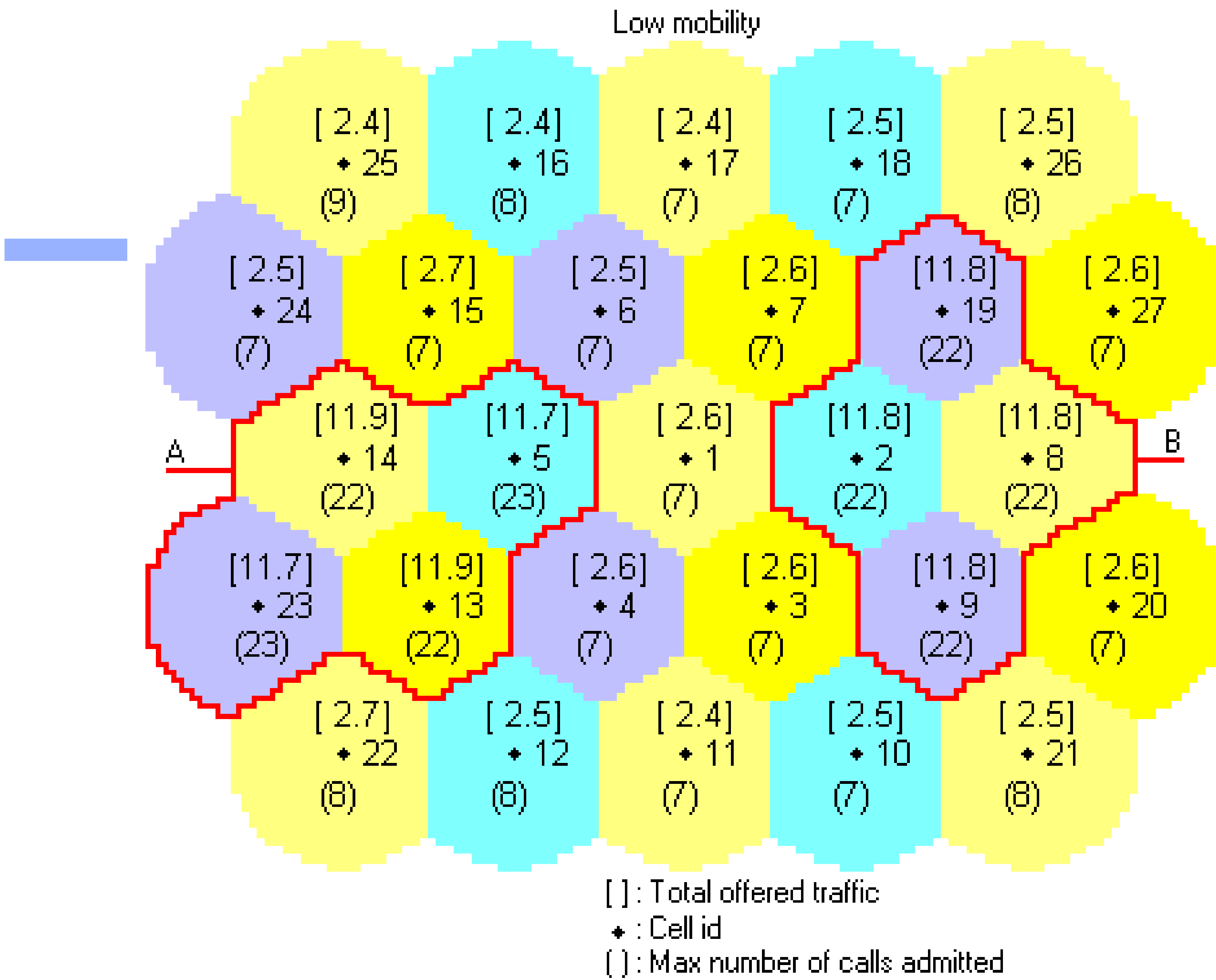

Low mobility
[2.4] ✦ 25 (9)
[2.4] ✦ 16 (8)
[2.4] ✦ 17 (7)
[2.5] ✦ 18 (7)
[2.5] ✦ 26 (8)
[2.5] ✦ 24 (7)
[2.7] ✦ 15 (7)
[2.5] ✦ 6 (7)
[2.6] ✦ 7 (7)
[11.8] ✦ 19 (22)
[2.6] ✦ 27 (7)
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[11.9] ✦ 14 (22)
[11.7] ✦ 5 (23)
[2.6] ✦ 1 (7)
[11.8] ✦ 2 (22)
[11.8] ✦ 8 (22)
B
[11.7] ✦ 23 (23)
[11.9] ✦ 13 (22)
[2.6] ✦ 4 (7)
[2.6] ✦ 3 (7)
[11.8] ✦ 9 (22)
[2.6] ✦ 20 (7)
[2.7] ✦ 22 (8)
[2.5] ✦ 12 (8)
[2.4] ✦ 11 (7)
[2.5] ✦ 10 (7)
[2.5] ✦ 21 (8)
[ ] : Total offered traffic
✦ : Cell id
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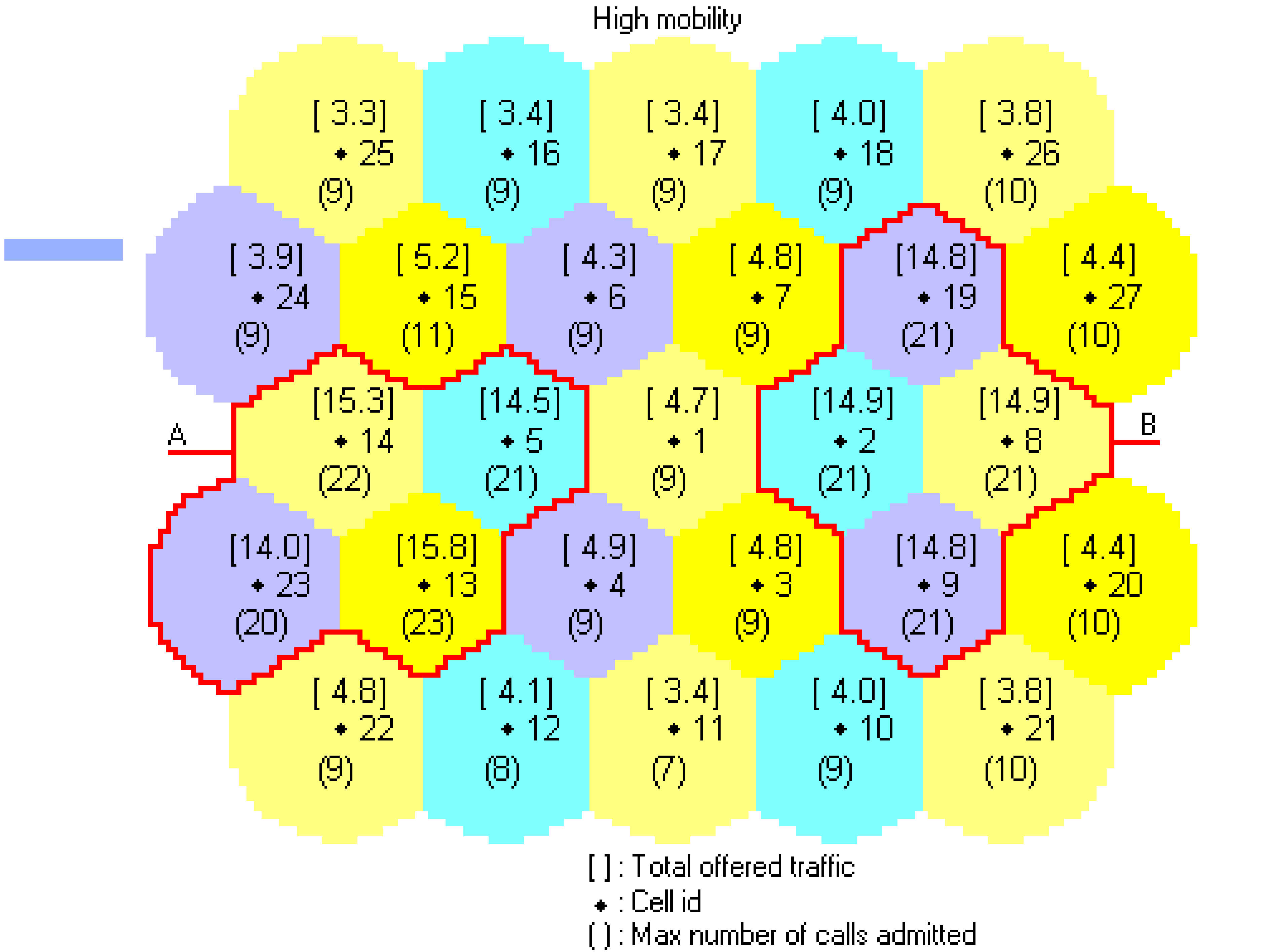
High mobility
[3.3] • 25 (9)
[3.4] • 16 (9)
[3.4] • 17 (9)
[4.0] • 18 (9)
[3.8] • 26 (10)
[3.9] • 24 (9)
[5.2] • 15 (11)
[4.3] • 6 (9)
[4.8] • 7 (9)
[14.8] • 19 (21)
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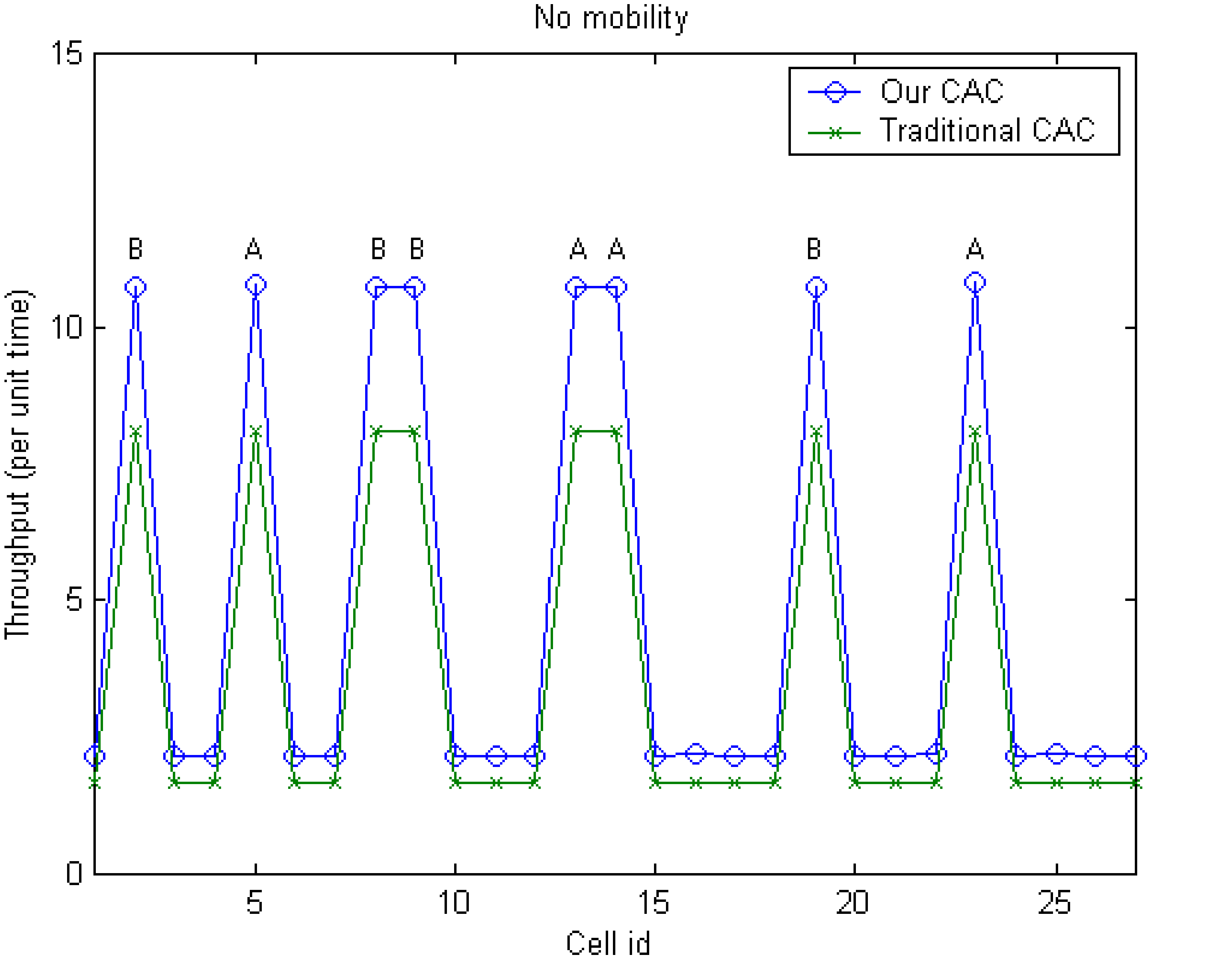
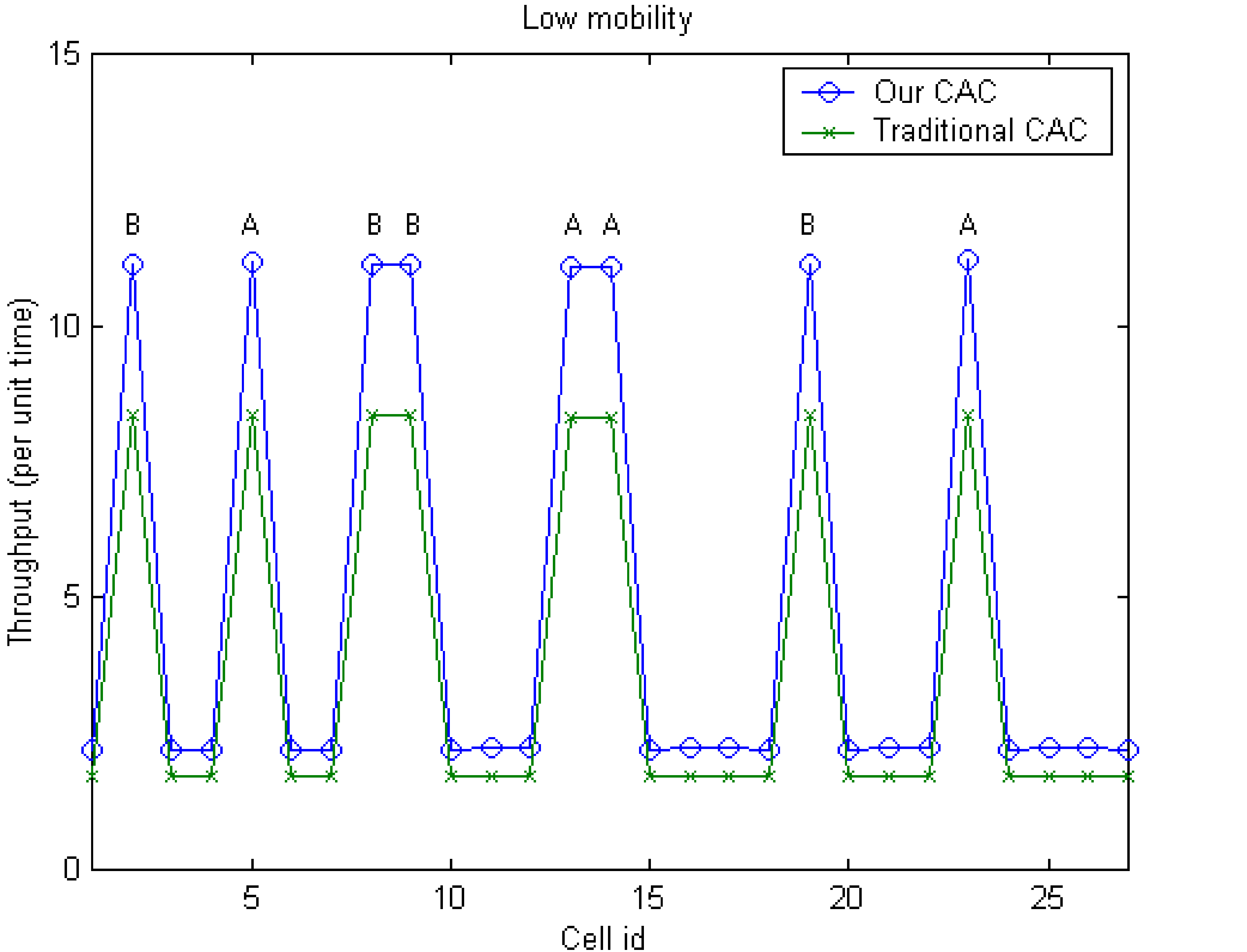
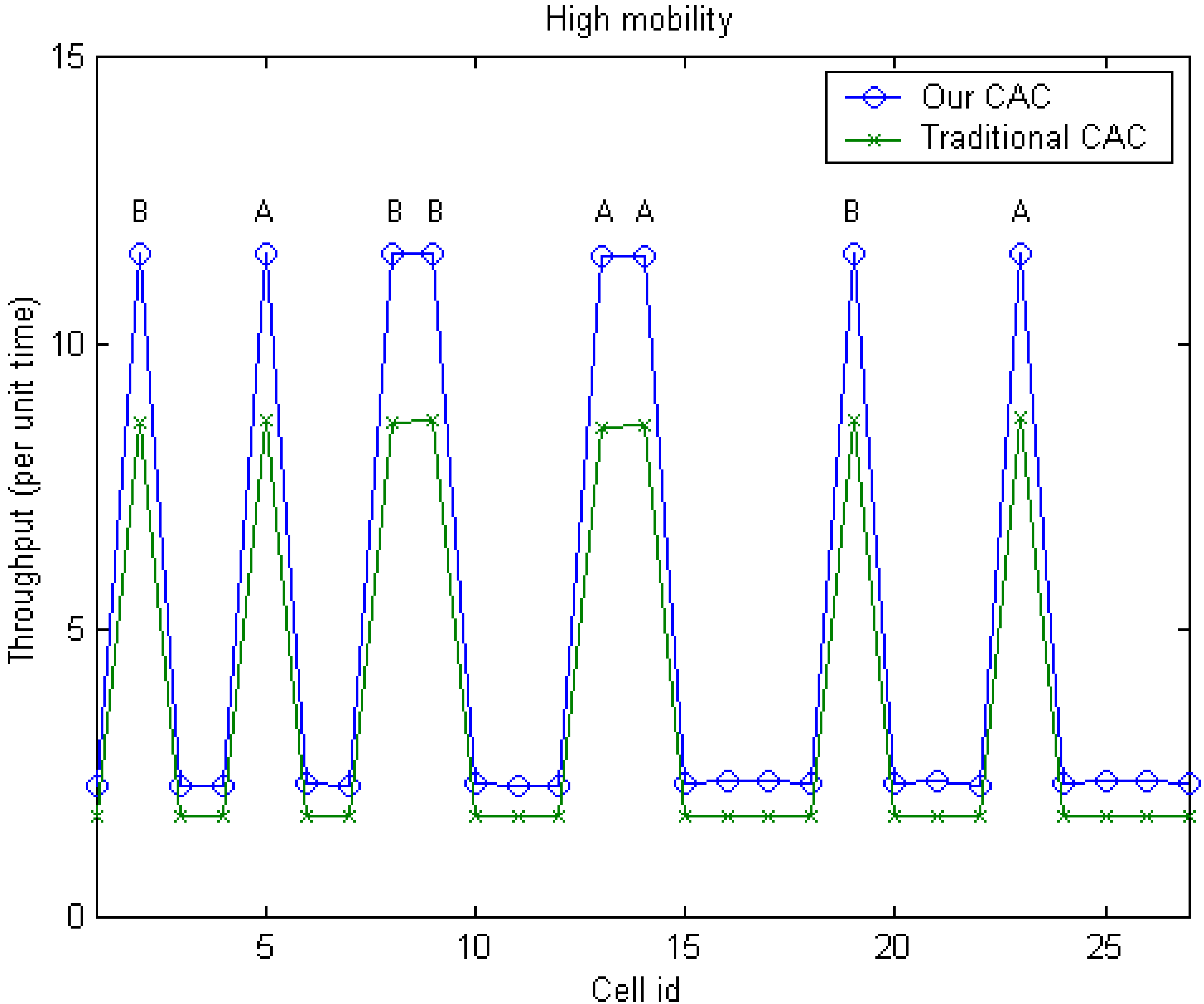
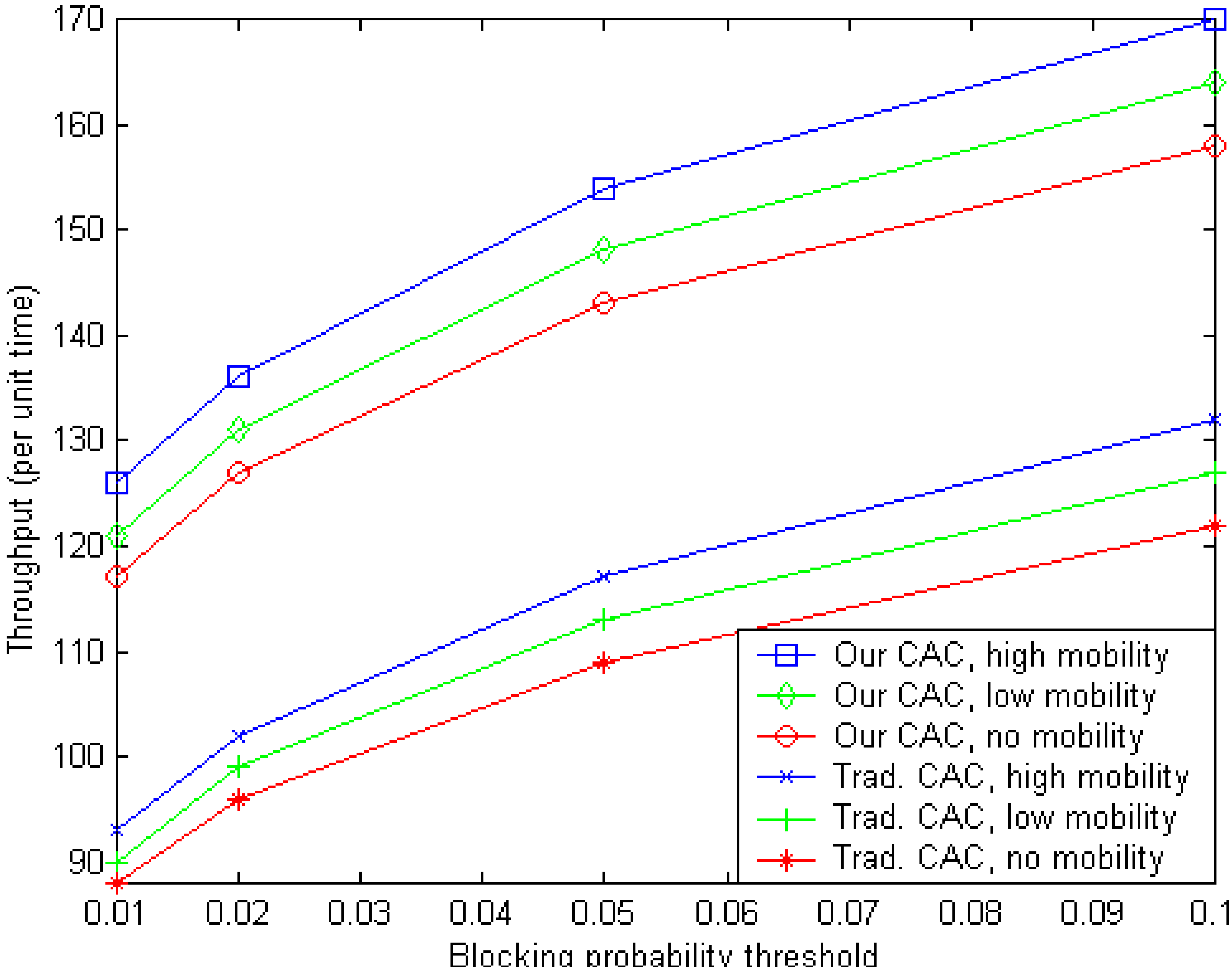
[15.3] • 14 (22)
[14.5] • 5 (21)
[4.7] • 1 (9)
[14.9] • 2 (21)
[14.9] • 8 (21)
B
[14.0] • 23 (20)
[15.8] • 13 (23)
[4.9] • 4 (9)
[4.8] • 3 (9)
[14.8] • 9 (21)
[4.4] • 20 (10)
[4.8] • 22 (9)
[4.1] • 12 (8)
[3.4] • 11 (7)
[4.0] • 10 (9)
[3.8] • 21 (10)
[ ] : Total offered traffic
• : Cell id
( ) : Max number of calls admitted



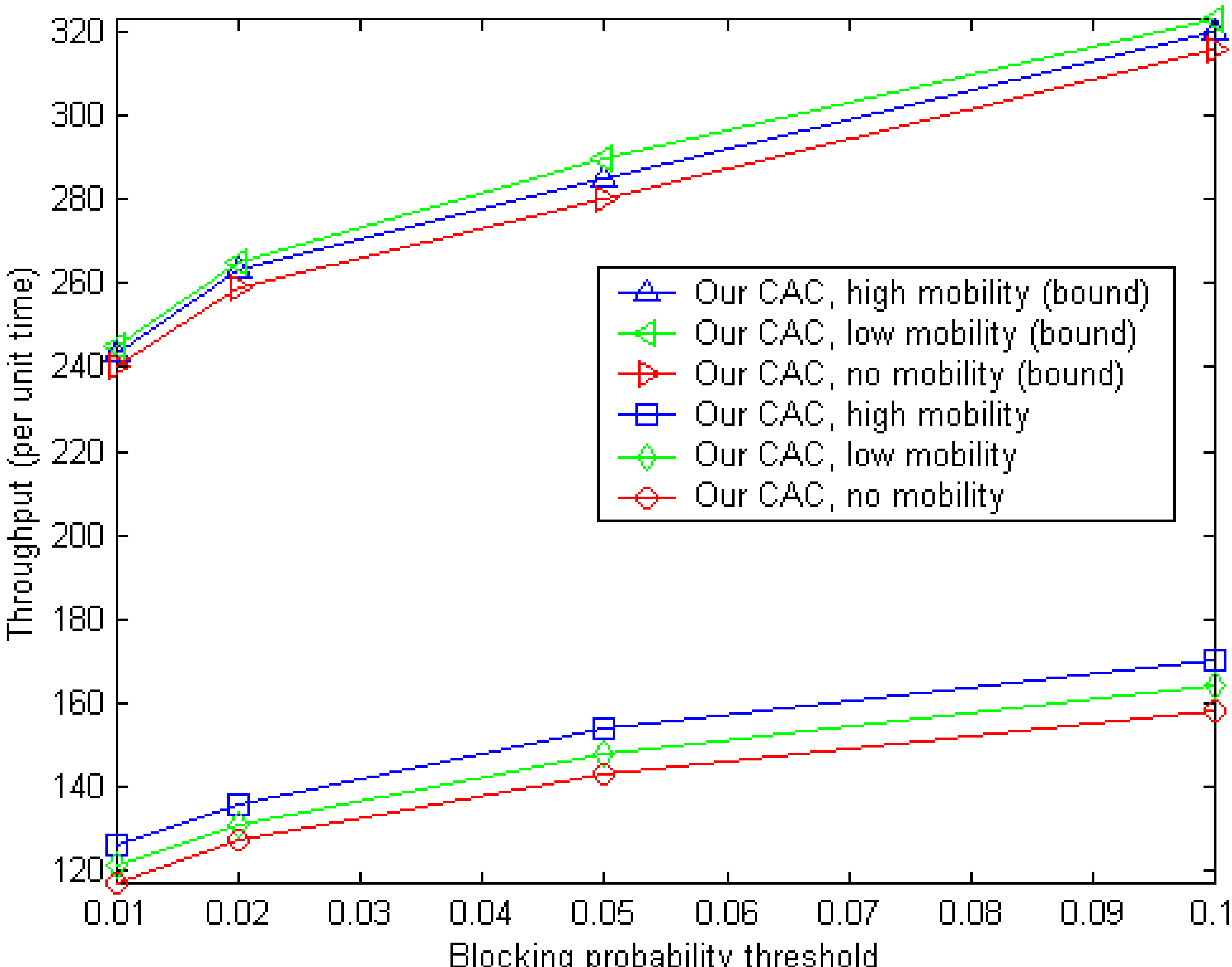
No mobility
Our CAC
Traditional CAC
B
A
B
B
A
A
B
A
Throughput (per unit time)
Cell id
0
5
10
15
5
10
15
20
25


Low mobility
Our CAC
Traditional CAC
B
A
B
B
A
A
B
A
Throughput (per unit time)
Cell id
0
5
10
15
20
25


High mobility
Our CAC
Traditional CAC
B
A
B
B
A
A
B
A
Throughput (per unit time)
Cell id
0
5
10
15
5
10
15
20
25



170
160
150
140
130
120
110
100
90
Throughput (per unit time)
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Blocking probability threshold
Our CAC, high mobility
Our CAC, low mobility
Our CAC, no mobility
Trad. CAC, high mobility
Trad. CAC, low mobility
Trad. CAC, no mobility



320
300
280
260
240
220
200
180
160
140
120
Throughput (per unit time)
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Blocking probability threshold
Our CAC, high mobility (bound)
Our CAC, low mobility (bound)
Our CAC, no mobility (bound)
Our CAC, high mobility
Our CAC, low mobility
Our CAC, no mobility

Conclusions

- **Solved cell design problem.**
- **Formed general principles on cell design.**
- **Designed a call admission control algorithm.**
- **Calculated upper bounds on throughput for a given network topology and traffic distribution profile.**