Fixed channel allocation

- C channels in the system
- Cell radius is $R$
- Interference from neighboring cells is assumed to be
  - Worst case
  - Scaled down by the average channel occupancy (mean traffic)
- For given service probability, we need to define the reuse distance $D$ between the cells
- The reuse distance defines the cluster size $K$
  - For hexagonal cell layout
- The number of channels available for the cell $c = C/K$
Fixed Channel Allocation

Dowlink interference

Downlink interference

Fixed Channel Allocation

Reuse factor in the different regions

Table 4.5. Reuse pattern size in different regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Quadratic cell structure</th>
<th>Hexagonal cell structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>(D/R)_{min}</td>
<td>(D/R)_{min}</td>
</tr>
<tr>
<td>1</td>
<td>1.732</td>
<td>1.732</td>
</tr>
<tr>
<td>2</td>
<td>2.000</td>
<td>2.000</td>
</tr>
<tr>
<td>3</td>
<td>2.828</td>
<td>2.828</td>
</tr>
<tr>
<td>4</td>
<td>3.162</td>
<td>3.162</td>
</tr>
<tr>
<td>5</td>
<td>4.000</td>
<td>4.000</td>
</tr>
<tr>
<td>6</td>
<td>4.243</td>
<td>4.243</td>
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<tr>
<td>7</td>
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<tr>
<td>8</td>
<td>5.099</td>
<td>5.099</td>
</tr>
<tr>
<td>9</td>
<td>5.831</td>
<td>5.831</td>
</tr>
<tr>
<td>10</td>
<td>6.000</td>
<td>6.000</td>
</tr>
<tr>
<td>11</td>
<td>6.325</td>
<td>6.325</td>
</tr>
<tr>
<td>12</td>
<td>6.671</td>
<td>7.071</td>
</tr>
<tr>
<td>13</td>
<td>7.000</td>
<td>7.071</td>
</tr>
<tr>
<td>14</td>
<td>7.211</td>
<td>7.211</td>
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<tr>
<td>15</td>
<td>7.616</td>
<td>7.616</td>
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<tr>
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<tr>
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<td>9.000</td>
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<tr>
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<td>9.165</td>
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<tr>
<td>20</td>
<td>9.644</td>
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<tr>
<td>21</td>
<td>10.392</td>
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</tr>
<tr>
<td>22</td>
<td>10.536</td>
<td>10.536</td>
</tr>
</tbody>
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Fixed Channel Allocation

DL service probability vs. reuse distance with six CCIs

Table 4.5. Reuse pattern size in different regions.

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Fixed and dynamic channel allocation

- Fixed channel allocation typically leaves to conservative designs (worst case analysis or mean traffic analysis) using large reuse distance D and large cluster size K.
- This in turn implies that the number of channels available in the cells is going to be small.
- In practice, both the interference power and traffic volume in the system fluctuates and the loading among the cells become unequal. In such case, it would be beneficial to reallocate channels from lightly loaded cells to the heavily loaded ones in order to minimize blocking and dropping.
- The idea of dynamic channel allocation is to redistribute the channel resources among the cells dynamically based on the instantaneous capacity demands.

Fixed and dynamic channel allocation

- Two cell system.

![Graph showing blocking probability vs offered traffic for FCA and DCA with 10 channels per cell](image-url)
Classification of DCA

Dynamic channel allocation

- Ideal channel allocation scheme would have knowledge on the instantaneous load (number of users) in each cell, received signal quality of the users as well as interference coupling among the cells.
- This would however, require centralized processing which due to signaling restrictions and delays would be difficult.
- Centralized schemes provide knowledge on the performance bounds.
- Practical implementation calls for distributed DCA schemes that make the decision based on locally available information.
FCA and DCA

- Practical DCA schemes have good performance when the traffic distribution is uniform and the traffic load is low. For high traffic intensity, FCA based on worst case analysis becomes optimal.

- **Slow DCA**
  - Resource allocation among the cells is adapted based on long term statistics of the load and interference.
  - Required signaling load is small, but resources are not always distributed in optimal manner.
  - Resembles network optimization process

- **Fast DCA**
  - Resource allocations among the cells are done at the time scale of the calls.
  - Requires a lot of signaling. Due to signaling restrictions the resource sharing is typically limited to some local neighborhood of cells – e.g. those controlled by the same BSC.

DCA
Traffic adaptive DCA

- In traffic adaptive DCA, one tries to adapt the allocation of spectral resources among the cells in accordance with the current measured number of active mobiles in each cell.
- A purely traffic adaptive DCA uses the same kind of interference analysis than static network planning (FCA).
- Instead of splitting the channels into equally sized channel groups, the size of each group is chosen to minimize the number of assignment failures.

Traffic adaptive DCA

- Assume that the number of channels in the system is C.
- Assume further that the channel plan suggest cluster size K to be used.
- If the number of channels is divided evenly, then there will be $c=C/K$ channels per cell.
- Assume that the number of users in cell i is $r_i$.
- Let $Z_i$ denote the number of channels assigned to cell i.
Compatibility

- Based on the required SINR and topology, a set of incompatible frequency cell allocations can be formed:
  \[ \mathcal{C} = \{ (i, j), (i', j') : |i - j'| < c_{ij}, (i, j) \neq (i', j') \} \]

- If \((i, j), (i', j') \in \mathcal{C}\) then frequency \(f_i\) cannot be assigned to cell \(j\) and frequency \(f_i'\) to cell \(j'\).
- \(c_{ij}\) denotes the required frequency spacing between cells \(i\) and \(j\):
  - If \(c_{ij} = 1\), frequency bands are orthogonal
  - If \(c_{ij} > 1\), guard bands are needed between the frequencies due to adjacent channel interference

In practice, the adjacent channels interfere with each other and we would like to have \(c_{ij} = 2\) or more.

Compatibility

- \(N\) Cells
- Interference graph
  - \(c_{ij} > 0\) if cells \(j\) and \(j'\) cannot utilize the same frequencies. That is, the separation between the cells is less than the reuse distance \(D\).
  - \(c_{ij} = 0\) if cells \(j\) and \(j'\) can utilize the same frequencies. That is, the separation between the cells is larger than the reuse distance \(D\).
  - \(c_{ij} = 1\)

Example \(D=2R\)
Requirement and service

- M frequencies
- Service matrix S
  - \( s_{ij} = 1 \) if frequency \( f_i \) is assigned to cell \( j \); otherwise \( s_{ij} = 0 \)
- Number of channels required in cell \( j \), \( r_j \), depends on the active number of calls in progress.
- Frequency assignment is successful if \( \sum_j s_{ij} \geq r_j \)

Maximum service/ minimum assignment failure problem

- **Maximum Service**

\[
\begin{align*}
\min & \sum_{j=1}^{N} \left( r_j - \sum_{i=1}^{M} s_{ij} \right) \\
\text{s.t.} & s_{ij} + s_{i'j'} \leq 1, \text{ for all } (i, j), (i', j') \in C, \\
& \sum_{i=1}^{M} s_{ij} \leq r_j, \quad j = 1, 2, \ldots, N, \\
& s_{ij}, s_{i'j'} \in \{0, 1\}, \text{ for all } i, j, i', j'.
\end{align*}
\]

- \( C = \{(i, j), (i', j') \text{ where } |i - i'| < r_{ij}, i \leq \hat{i}, (i, j) \neq (i', j')\} \)
- Pure 0-1 IP
Greedy algorithm

- If the ones in the compatibility matrix forms a band on the diagonal, then the minimum assignment failure problem can be solved using a simple greedy algorithm.

- In general case, the problem becomes NP complete and cannot be efficiently solved.

Let $A_i$ denote the number of channels assigned to cell $i$, $i=1,2,...B$

Greedy channel allocation algorithm:
1. $A_1 = \min(r_1,C)$
2. $Y_i = C - \sum_{j=1}^{i-1} c_{ij} A_j$
3. $A_i = \min\{r_i, Y_i\}$

Example

- Cell plan
- FCA:
  - Cluster size $K=3$
  - Number of channels $C=18$
  - Number of channels per cell $C/K=6$
  - Assignment $A=[6,6,6,6,6,6]$
  - Requirement vector $r=[7,6,6,4,8,6]$
  - Assignment failure $Z=\max(0,r-A)=[1,0,0,0,2,0]$
  - Two calls are blocked
**Example**

- **DCA**
  - Requirement vector \( r = [7, 6, 6, 4, 8, 6] \)
    - \( A_1 = \min(C, r_1) = \min(18, 7) = 11 \)
    - \( Y_2 = C - A_1 = 18 - 7 = 11 \)
    - \( A_2 = \min(Y_2, r_2) = 6 \)
    - \( Y_3 = Y_2 - A_2 = 11 - 6 = 5 \)
    - \( A_3 = \min(Y_3, r_3) = 2 \)
    - \( Y_4 = Y_3 - A_3 = 5 - 2 = 3 \)
    - \( A_4 = \min(Y_4, r_4) = 3 \)
    - \( Y_5 = Y_4 - A_4 = 3 - 3 = 0 \)
    - \( A_5 = \min(Y_5, r_5) = 0 \)
    - \( Y_6 = Y_5 - A_5 = 0 - 0 = 0 \)
    - Assignment failure \( Z = \max(0, r - A) = [0, 0, 0, 0, 0, 0] \)

\[
C = \begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

**Channel Borrowing**

- Traffic adaptive DCA can be implemented as channel borrowing scheme.
- A fixed channel allocation for the network is assumed to exist. This defines the set of nominal channels available for each cell.
- A cell having high load is allowed to borrow a channel from another channel group.
- This channel needs to be locked in the neighboring cells such that the interference constraints are met.
- Also reassignment of the channel is possible when one of the nominal channels becomes available due to call departure.

**Example.** The middle cell borrows a channel from the red channel group.
Channel Borrowing

- Many different algorithms have been proposed: Borrow from the Richest, Borrow from First available, ...
- Channel borrowing schemes work well in light load conditions, but the channel locking property can drastically decrease the system performance on heavy loads.
- In practice due to the complexity simple schemes work the best.
- Hybrid channel borrowing schemes divide the nominal channels into two sets: A) Standard and B) Borrowable.
- The ratio between A and B channels could be either set based on the traffic statistics or could be dynamically adjusted based on load.

Interference adaptive DCA

- The compatibility matrix is based on pair-wise comparison and does not take into account the interference from other cells. Not knowing the interference level forces the designer to use large safety margins.
- In dynamic channel allocation, a cell will measure the signal level in each channel and then make decisions whether to use it or not.
- Reassignment of channel is triggered if the communication quality at the current channel falls below some pre-defined threshold.
- In totally distributed dynamic channel selection scheme, the decision is done locally without any knowledge of the other cells. The channel selection procedure resembles inter-frequency handover procedure.
Interference adaptive DCA

- Simple sequential channel selection scheme:
  - If the SINR of the current channel $i$ falls below some threshold $\gamma_c$, the system starts DCA procedure.
  - Interference (total received signal power) at different bands is observed and estimates the achievable SINR based on the current received signal strength. If SINR at some different band is larger than some threshold value $\gamma_k > \gamma_c$, the system makes inter-frequency handover and starts using this new band.
- More complex variant of the scheme, would measure the SINR on all band and select the one with the highest.

\begin{align*}
S_{ij} &= \frac{g_{sb} P_j}{g_{sb} P + \sigma^2} < \gamma_c \\
S_{kj} &= \frac{g_{sb} P}{g_{sb} P + \sigma^2} \geq \gamma_c
\end{align*}

Example

- Two cells (b and b')
- Two channels (i and i')
- SINR at base station b
  - $\Gamma_{bi} = \frac{g_{sb} P_i}{g_{sb} P + \sigma^2}$
  - If both cells choose the same channel we have $\Gamma_{bi} = \frac{g_{sb} P}{g_{sb} P + \sigma^2} < \gamma_c$
  - Channel i' has SINR equal to $\Gamma_{bi'} = \frac{g_{sb} P}{\sigma^2} \geq \gamma_c$
  - This would imply that both users jump to channel i' which then once again sees bad SINR ($\gamma_c$)
  - The allocation strategy never converges!
Autonomous DCA

- The channel segregation scheme avoids the possible deadlocks by applying learning
  - The algorithm is
    - Fully distributed
    - Adaptive to traffic changes
    - Decreases the load to switching system
    - Reduce interference due to carrier sense
    - Reduce blocking probability
    - Quickly reaches sub-optimal allocation
    - Is not guaranteed to find optimal allocation


\[ P_i = \frac{N_{idle}}{N_{busy} + 1} \]

- \( P_i \): denotes channel selectability
- \( N_i \): denotes the number of times that channel \( i \) has been used by the base station
- New call is assigned to the channel with highest \( P_i \)
- Before the assignment, the system measures the channel power. If the received power is below some threshold, the channel is considered to be idle and its \( P_i \) value is increased. If the channel is not idle, then the \( P_i \) value is decreased and the algorithm proceeds to the next highest value of \( P_i \)
- If no channels are available, then the call is blocked.

\[
P_i = \begin{cases} 
\frac{N_i + 1}{N_{idle}} & \text{channel is idle} \\
\frac{N_i}{N_{busy} + 1} & \text{channel is busy}
\end{cases}
\]

\[
x_i = \begin{cases} 
x_i + 1 & \text{channel is idle} \\
x_i - 1 & \text{channel is busy}
\end{cases}
\]
**Autonomous DCA**

- Radio Resource Management Methods 3 op
- TKK Communications Laboratory

**Dynamic spectrum access**

- Radio spectrum is a scarce resource
- Upcoming broadband services require a lot of bandwidth (100 MHz for 4G)
- Recent measurements indicate that certain frequency-time-space chunks are currently underutilized by the license holders
- Dynamic spectrum access (DSA):
  - A secondary user could access a band provided that it is free.
  - Multiple systems can compete for the frequency band (license exempt bands)
- Cognitive radio: Radio is able monitor the spectrum and make decisions what resources to use dynamically.
### Dynamic spectrum access

#### DCA
- Frequency allocation within single radio access network.
- Network topology is known in advance
- Co-operative algorithms and centralized operation is possible
- Channel borrowing and locking
- Mature field. Lots of algorithms exist.

#### DSA
- Frequency allocation among multiple networks.
- Network topology is not known and can change dynamically
- Competitive algorithms are needed. Decentralized algorithms must be used.
- Absence of primary user must be detected. No possibility to lock channels. Resources must be freed if primary user is detected.
- A hot research topic.

---

### Dynamic spectrum access

- There are certain fundamental limits in the cognitive radio approach.
  - Detection of weak signals is impossible if the noise power is not known accurately.
  - Accurate power detection requires a lot of measurements. => Monitoring the bandwidth consumes a lot of time and energy.
  - Only transmitters can be detected, but the system should protect received SINR. (Hidden and exposed node problems)

- To overcome this difficulties
  - Dynamic spectrum access can be utilized in cellular setting where multiple operators share some fractions of the bandwidth.
    - Waveforms are known as well as part of the system topology
    - Centralized control is possible in form of spectrum and access brokerage
  - Cognitive pilot and signaling channels can be utilized
    - Signal detection would not be the limiting factor
      - IEEE 1900 SCC41, IEEE 802.22