S-72.333
Postgraduate Course in Radio Communications
2002-2003

Hierarchical Cell Structures in CDMA Systems

Kimmo Hiltunen, 39195V
Kimmo.Hiltunen@ericsson.fi
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1 INTRODUCTION

During initial system deployment the majority of WCDMA system operators will focus upon providing radio bearer coverage and quality of service. As the network matures, the focus will broaden to include system capacity. In urban areas where the demand for capacity is especially high and site acquisition is particularly difficult, multi-layered network deployment becomes an attractive solution. The term “multi-layered network” represents network deployments that are build on multiple (hierarchical) cell layers. The different layers are characterized by features like cell carrier, size, output power, antenna position and so on. Three main types of layers having commonly accepted features can be found in the literature: macro, micro and pico layers. The different cell types enable an efficient and flexible handling of traffic with different characteristics in terms of service and mobility. For instance, macrocells are suitable for ensuring continuous coverage and handling low capacity terminals with high mobility. Microcells, which are necessary to achieve good spectral efficiency, can be designed to handle high capacity terminals with low mobility in highly populated areas. Finally, picocells, deployed in indoor environment, can serve many terminals with very low mobility. One of the main challenges for the radio network planning process is to achieve full connectivity between cells belonging to different layers, while maximizing the total system capacity.

This paper will mainly focus on a WCDMA hierarchical cell structure (HCS) consisting of macro and microcells.

2 WCDMA SYSTEM EVOLUTION SCENARIO

The number of FDD carriers affects the operators’ WCDMA network deployment scenarios, and the use of HCS scenarios. To start operating the network, the operator would typically begin with just one carrier deployed on a macrocellular layer to provide continuous coverage. This applies especially to a greenfield operator who cannot rely on an existing GSM network for coverage. Later, a second carrier (and possibly more) is deployed to enhance the capacity.

The second carrier can be added to the macrocellular layer to create high-capacity sites or it can be used to build a micro layer. In its first phase, the micro layer is typically deployed only in traffic hot-spots or where high bit rates are needed. Furthermore, micro cells can be used to fill coverage holes (black spots) within the macro layer. Finally, in later phases of the network deployment, continuous microcellular coverage within a specific area may be required, and if further capacity is needed more carriers must be deployed, using either a new frequency if available, or reusing a carrier that has already been used in another layer. An example of a possible WCDMA network evolution path is shown in Figure 1.

The required capacity and coverage trade-off needs to be carefully considered. Typically, within the HCS in a WCDMA network, the micro layer provides a very high capacity in a limited area, whereas the macro layer can offer full coverage but with smaller throughput.
Another important issue is whether the network should be able to support mobiles moving at high speed. If there is no such need, the easiest way to continue is to sacrifice the macro layer and put both frequencies to the micro layer. This alternative might, however, result in increased investment, which has to be carefully evaluated. On the other hand, if a pure microcellular network has to support high-mobility users, there would be too many handovers between the cells. Therefore, it is always beneficial to have an “umbrella” macro layer reserved for such users. Then the strategy to increase capacity further is to reuse one frequency in the other layer.

3 SOME NETWORK OPERATION ASPECTS

3.1 INTERFERENCE

It is impossible to consider any part of a WCDMA system in isolation. Changes to a part of the system may include changes over a large area. In WCDMA, system capacity and coverage are typically limited by the uplink and/or downlink interference. In uplink the interference comes from all the other mobile stations, and in downlink from the neighboring base stations. Although the number of downlink interference sources is low, the interference power is relatively high. Furthermore, the interference power level depends typically on the location of the user. Finally, downlink interference level is relatively high also in a low loaded system, since the base stations always have to transmit the downlink common channels.

In downlink, the total transmitted power is shared between the users. In uplink, there is a maximum interference level tolerable at the base station receiver. Each user contributes to the total interference, which is then shared between all users in the cell. If the performance of some links can be improved, the required transmission power levels in both uplink and downlink, and as a result of that, the total interference are
immediately reduced. In the end, this reduced interference level results in improved capacity, coverage or link quality.

### 3.2 Pilot Power Adjustment

Power allocation for the downlink Common Pilot Channel (CPICH) is another very important task in the WCDMA network design. Optimum pilot powers ensure coverage with minimum interference to the neighboring cells. Excessive pilot powers will easily reserve too large a portion of the total available base station transmission power so that not enough power is left for the traffic channels. Furthermore, the cell can collect distant users, which do not necessarily have enough mobile transmission power to connect to the base station, and would be more optimally served by some other base station. On the other hand, pilot powers that are too low may not provide wide enough pilot coverage, and result in smaller coverage areas than planned. Finally, if link-power limits are set with respect to the pilot levels, low pilot powers also restrict link powers. Typically, approximately 5-10% of the maximum base station power is allocated to the pilot channel, and roughly the same amount to other common channels.

If a mobile is in location where several pilots are received with roughly equal signal strengths, it may happen that none of the pilot signals is dominant enough to enable the mobile to start a call. Pilot coverage from neighboring base stations must overlap in cell border areas to accommodate handovers. However, each cell that has significant power within the soft handover area will increase the total interference power and decrease the CPICH $E_c/N_0$ (energy of the pilot signal divided by the total channel power) for the dominant CPICH. The total channel power includes the total received power from all base stations and the thermal noise. Receiving too many pilot signals can degrade both the capacity and quality, and can be prevented by proper network planning. It is essential to create a network plan, where cells have clear dominance areas [1].

### 4 HCS Deployed on a Single Carrier

A solution where macro and microcells operate on the same carrier frequency can be also called as Embedded Microcells. There, cells belonging to different layers are separated by spatial isolation, and soft handover is enabled between the layers. This solution aims at maximizing the system capacity in case of non-homogeneous traffic demand. The service area of the micro base station, situated below the rooftops, is surrounded by the service area of a macro base station, situated above the rooftops. The service areas, with the exception of the soft handover zone, are disjointed, and full connectivity between the layers is guaranteed by the soft handover itself.

System capacity gain depends to a great extent on the isolation achieved between the different layers. Isolation can be improved by:

- Placing the microcells so that most of the users in its service area have line-of-sight propagation conditions towards the serving base stations.

---

1 In case of embedded microcells, it is imperative that mobiles active within the microcell area are not connected to the macrocell, in order to avoid possible system performance degradation due to inter-layer interference (i.e. near-far problems).
• Lowering the microcell antenna position and making use of the shadowing provided by the buildings, in order to limit the inter-layer interference.
• Increasing the spatial separation among base stations belonging to different layers.

Besides the isolation between layers, the overall capacity gain depends on the ability to plan microcells so that the service area is large enough to cover the hot spot traffic. This is due to the fact that the performance of the embedded microcell solution is sensitive to changes in the geographical traffic distribution. A traffic hot-spot expanding outside the microcell coverage area will partly be served by the macrocell, hence losing at least part of the spectral efficiency gain provided by the microcells.

4.1 MICROCELL BOUNDARY

In case of the downlink, the boundary between the macrocell and an embedded microcell is defined by the received CPICH. Since a normal soft handover algorithm is applied, the mobile can be defined to be at the border between two cells, when the received CPICH $E_c/N_0$ (or CPICH RSCP) is the same from both of them\(^2\). Thus, at the cell border the received CPICH RSCP can be expressed as

$$P_{Rx,CPICH} = \begin{cases} P_{CPICH,M} + G_M + G_{UE} - (A_M + 10\alpha_M \log(d_M)) \\ P_{CPICH,\mu} + G_\mu + G_{UE} - (A_\mu + 10\alpha_\mu \log(d_\mu)) \end{cases}$$  \hspace{1cm} (4.1)

where $P_{Rx,CPICH}$ is the received CPICH power [dBm], $P_{CPICH,M}$ is the transmitted CPICH power from the macro cell [dBm], $P_{CPICH,\mu}$ is the transmitted CPICH power from the micro cell [dBm], $G_M$ is the macro base station antenna gain [dB], $G_\mu$ is the micro base station antenna gain [dB], $G_{UE}$ is the mobile station antenna gain [dB], $A_M$ is the attenuation constant for the link towards the macro base station [dB], $A_\mu$ is the attenuation constant for the link towards the micro base station [dB], $\alpha_M$ is the attenuation factor for the link towards the macro base station [dB], $\alpha_\mu$ is the attenuation factor for the link towards the micro base station [dB], $d_M$ is the distance towards the macro base station [m], $d_\mu$ is the distance towards the micro base station [m].

Equation (4.1) leads to the following relationship

$$\left(\frac{d_M}{d_\mu}\right)^{\alpha_M} = 10^{\frac{1}{10}\left[\left(P_{Rx,CPICH,M} - P_{Rx,CPICH,\mu}\right) + (G_M - G_\mu) + (A_M - A_\mu)\right]}$$  \hspace{1cm} (4.2)

\(^2\) In fact, the specifications allow the use of cell individual offsets, which can be used to adjust the location of the cell border. Here, however, all cell individual offsets are assumed to be set to zero.
Thus, the key issues that determine the cell shape are the path loss exponents, CPICH transmission powers and the shape of the antenna beams. Furthermore, the size of the microcell depends on the distance from the overlaying macrocell. Figures 2 to 5 show in a simplified manner how the factors listed above contribute to the shape of the microcell.

![Figure 2. Effect of the path loss exponent on the microcell shape](image1.png)

Figure 2. Effect of the path loss exponent on the microcell shape
($P_{CPICH,M}=2$ W; $P_{CPICH,\mu}=0.2$ W)

![Figure 3. Effect of micro base station position on the microcell shape](image2.png)

Figure 3. Effect of micro base station position on the microcell shape
($P_{CPICH,M}=2$ W; $P_{CPICH,\mu}=0.2$ W, $\alpha_M=3.5$, $\alpha_\mu=5$).
By looking at the figures, the following observations can be made:

- The outward boundary of the microcell is farther away from the micro site than the inward boundary, as the difference in the slopes of the path loss curves is smaller.
- When $\alpha_\mu$ increases (e.g. as a result of lower antenna heights), the path loss curve becomes steeper, and the size of the microcell becomes smaller.
- The larger the distance between the macro and micro base stations, the larger the microcell.
- The larger the radio $\Delta = P_{CPICH,M}/P_{CPICH,\mu}$, the smaller the microcell.
- The shape of the microcell shape depends also on the directivity of the base station antennas. The effect of directivity is equivalent to the increase or decrease in transmission power in a certain direction, according to the antenna gain.
In Figure 6 the impact of the distance from the macro site and the antenna diagram on the shape and size of the microcell is visualized in a more efficient way. There, $\Delta$ is assumed to be equal to 10 dB, and the following path loss models are applied:

$$L_M = 20.4 + 38 \log_{10}(d_M) - 15 \quad [\text{dB}]$$  \hspace{1cm} (4.3)

$$L_\mu = 28 + 40 \log_{10}(d_\mu) - 5 \quad [\text{dB}]$$  \hspace{1cm} (4.4)

Furthermore, the impact of log-normal shadow fading is ignored. The dark areas surrounding the micro base stations describe the soft handover zones, assuming a soft handover window equal to 3 dB.

In an urban environment, buildings and other obstacles can be used to limit the inter-cell (micro-micro) and inter-layer (micro-macro) interference, still providing coverage where needed. For example, in case of building blocks forming straight street canyons, the signals can propagate along them for several blocks, while the microcell signal might not even be detectable in the street on the other side of a building. Figure 7 shows

**Figure 6.** Shape of the microcell as a function of the distance between the macro and the micro base station. Macro base station is marked with “o”.

**Figure 7.** Coverage area of a microcellular system deployed under a macrocellular system. Macro base stations are marked with “o”.

In an urban environment, buildings and other obstacles can be used to limit the inter-cell (micro-micro) and inter-layer (micro-macro) interference, still providing coverage where needed. For example, in case of building blocks forming straight street canyons, the signals can propagate along them for several blocks, while the microcell signal might not even be detectable in the street on the other side of a building. Figure 7 shows
the total coverage area of an microcellular system consisting of four base stations located under a macrocell.

From the uplink point of view the boundary between the cells is defined as the equilibrium point where the transmission power \( P_{Tx} \) required from the user by both cells is the same. Thus,

\[
P_{Tx} = \begin{cases} 
C_M - (G_M + G_{UE}) + A_M + 10\alpha_M \log(d_M) \\
C_\mu - (G_\mu + G_{UE}) + A_\mu + 10\alpha_\mu \log(d_\mu)
\end{cases}
\]  

(4.5)

where \( C_M \) is the required carrier power at the macro base station [dBm], and \( C_\mu \) is the required carrier power at the micro base station [dBm].

According to [2] balancing between uplink and downlink is recommended, in order to ensure smooth handover and to avoid orphan cases, where the mobile could be better covered by one cell but better received by another one. However, exact link balancing is not achievable at all times, for example due to traffic variations. Still, some rough (average) balancing can be appropriate.

Considering both the uplink and downlink, the following equations can be written:

\[
C_M - G_M + L_M = C_\mu - G_\mu + L_\mu 
\]  

(4.6)

\[
P_{CPICH,M} + G_M - L_M = P_{CPICH,\mu} + G_\mu - L_\mu 
\]  

(4.7)

where \( L_M \) and \( L_\mu \) are the path losses towards the macro and micro base station, respectively. When the equations are combined, the following link balancing relationship is obtained:

\[
P_{CPICH,M} - P_{CPICH,\mu} = C_\mu - C_M 
\]  

(4.8)

### 4.2 DESENSITIZATION

As described in [3] the minimum coupling loss (MCL) between the cell site and the mobile depends on the cell-site antenna height and its gain. The MCL is roughly equal to 70 dB for macrocells, while for micro and picocells, where the antenna heights are much lower, the MCL is approximately 53 and 45 dB, respectively.

Such a low transmission loss makes the cell-site receiver susceptible to interference from various sources and to saturation by nearby units. It could therefore be necessary to desensitize the microcell. However, the amount of desensitization required is less than the excess coupling due to the lower antenna placement of the microcell [2]. A cell can be desensitized by increasing the noise figure of the receiver, or by adding an attenuator.

The downside of the desensitization is that it increases the average mobile transmit power within the microcell. As a result of that, the uplink interference from the microcell towards other co- and adjacent channel cells and systems increases, resulting for example in a lower macrocell capacity. Desensitization affects also the range of the
microcell for a given mobile station transmit power, but capacity rather than range is the primary issue considered in the design of a microcell.

4.3 UPLINK CAPACITY OF MACROCELL/MICROCELL

Assume the simplified scenario shown in Figure 8. There, the macrocell layer consists of omnidirectional macrocells with radius $R$, each one uniformly loaded by the same number of users, $M$. Furthermore, a single (circular) microcell with radius $r$ and the number of users equal to $K$ is deployed under one of the microcells.

![Figure 8. Assumed system scenario [4].](image)

Assuming now a single service system with perfect and unconstrained power control, the received carrier power at the serving (primary) base station is the same for all users. In this paper, $C_M$ is the received carrier power at the macro base station, while $C_m$ is the received carrier power at the micro base station. Now, the total interference powers at the macro and the micro base station can be approximated as

\[
I_M = MC_M (1 + F_{MM}) + KC_M F_{\mu M} + N_M
\]

(4.9)

\[
I_\mu = KC_\mu + MC_M F_{M\mu} + N_\mu
\]

(4.10)

where $F_{MM}$ is the macrocell-to-macrocell interference factor, $F_{\mu M}$ is the microcell-to-macrocell interference factor, and $F_{M\mu}$ is the macrocell-to-microcell interference factor [4]. The interference factors will depend e.g. on the microcell shape and size, the distance $D$ between the macro and microcell and the propagation characteristics.

For a single layer system, the following uplink pole capacities can be obtained:

\[
M_0 = \frac{1}{1 + F_{MM}} \cdot \frac{1}{1 + \frac{1}{\rho_M}}
\]

(4.11)

for the macrocell, and
for the microcell. Keeping in mind that \( C_M = \rho_M (I_M - C_M) \) and \( C_\mu = \rho_\mu (I_\mu - C_\mu) \) the capacity of the macrocell as a function of the number of users connected to the microcell can be solved as

\[
M_{\text{max}} = \frac{M_0}{1 + \frac{KF_\mu F_\mu}{(K_0 - K)(1 + F_{MM})}} \tag{4.13}
\]

and the capacity of the microcell as a function of the number of users connected to the macrocell as

\[
K_{\text{max}} = \frac{K_0}{1 + \frac{MF_\mu F_\mu}{(M_0 - M)(1 + F_{MM})}} \tag{4.14}
\]

Equations (4.13) and (4.14) can be re-written using the relative capacities, \( \eta_M = M/M_0 \) and \( \eta_\mu = K/K_0 \) (see Figure 9, where it is assumed that \( F_{MM} = 0.6, F_{\mu M,0.4} = 3.8 \times 10^{-2}, F_{\mu M,1.0} = 5.9 \times 10^{-4}, F_{M\mu,0.4} = 3.5 \) and \( F_{M\mu,1.0} = 14.58 \) [4]):

\[
M_{\text{max}} = \frac{M_0}{1 + \frac{F_{\mu} F_\mu}{(\eta_\mu^{-1} - 1)(1 + F_{MM})}} \tag{4.15}
\]

\[
K_{\text{max}} = \frac{K_0}{1 + \frac{F_{\mu} F_\mu}{(\eta_M^{-1} - 1)(1 + F_{MM})}} \tag{4.16}
\]

Figure 9. The relative load in the macrocell versus the relative load in the microcell \( (r = 0.2R, D = (0.4, 1)R) \).
Finally, the equations estimating the uplink noise rise can be written as

\[
\frac{I_M}{N_M} = 1 + \frac{KF_{\mu M}N_\mu}{(K_0 - K)N_M} \quad \text{and} \quad 1 - \frac{M}{M_0} \left( 1 + \frac{KF_{\mu M}F_{\mu M}}{(K_0 - K)(1 + F_{MM})} \right)
\]

\[
1 - \frac{N_\mu}{N_M} = 1 + \frac{F_{\mu M}N_\mu}{(\eta_\mu^2 - 1)N_M} \quad \text{and} \quad 1 - \frac{M}{M_0} \left( 1 + \frac{F_{\mu M}F_{\mu M}}{(\eta_\mu^2 - 1)(1 + F_{MM})} \right)
\]

(4.17)

for the macrocell, and

\[
\frac{I_\mu}{N_\mu} = 1 + \frac{MF_{\mu M}N_M}{(M_0 - M)(1 + F_{MM})N_\mu} \quad \text{and} \quad 1 - \frac{K}{K_0} \left( 1 + \frac{MF_{\mu M}F_{\mu M}}{(M_0 - M)(1 + F_{MM})} \right)
\]

\[
1 - \frac{N_\mu}{N_M} = 1 + \frac{F_{MM}F_{\mu M}}{(\eta_\mu^2 - 1)(1 + F_{MM})}
\]

(4.18)

Assuming a certain maximum allowed values for the \(I_M/N_M\) and \(I_\mu/N_\mu\), the curves shown in Figure 10 can be obtained. There, it is assumed that \(N_\mu/N_M = 10\) (i.e. micro base station is assumed to desensitized by 10 dB) and \(D = 0.4R\). For example, it can be noticed that if the maximum allowed noise rise is 6 dB for both layers, in balanced scenario the relative loading level is 0.51 for the macro layer and 0.64 for the micro layer. Thus, the macro layer capacity suffers clearly more from the inter-layer interference than the micro layer capacity.

![Figure 10. Relative macrocell capacity as a function of the relative microcell load (left) and relative microcell capacity as a function of the relative macrocell load (right) assuming certain maximum noise rise levels.](image-url)

In this chapter only one microcell has been assumed. However, the analysis can be extended to the case of multiple microcells. That is, if microcells are sufficiently separated, the microcell-to-microcell interference can be ignored. However, if microcells are clustered, the microcell-to-microcell interference factor \(F_{\mu M}\) should be added in (4.10) as \(F_{MM}\) in (4.9). Furthermore, the values for \(F_{MM}\) and \(F_{\mu M}\) have to be adjusted based on the extended scenario with multiple microcells.
5 HCS DEPLOYED ON MULTIPLE CARRIERS

In this deployment the hierarchical cell layers are operating on different (in most of the cases adjacent) carrier frequencies, and the separation between the layers is provided by the receiver and transmitter filters. As a result is this, there is no hard requirement for disjoint service areas for the different layers. Thus, users located within the microcellular service area can still be connected to the macrocell for e.g. mobility or load sharing reasons. However, as pointed out in [3], some near-far problems may still exist due to the implementation imperfections in the transmitters and the receivers. For example, the micro base stations can be surrounded by downlink dead zones for the mobiles connected to an adjacent channel macro base station.

One of the main advantages of multi-carrier HCS deployment is the ability to have an overflow of traffic from one layer to an alternative one, based on specific capacity management and load sharing strategies. The connectivity among layers is ensured by the inter-frequency handover functionality. In a system with overflow capability, a blocked call can trigger a redirection to the other layer if the capacity limit in the original layer is reached. Besides that, a blocked intra-layer handover request can also trigger an overflow to the other layer. Finally, a significant change in speed can lead to an overflow as well.

As a consequence of the better resource sharing between macro and micro layers, the overflow capability can improve the system Grade of Service (GoS) metrics, i.e. blocking and dropping probabilities, which in the end leads to a higher system capacity. Furthermore, a careful selection of the mobiles to be overflowed can reduce the signaling load and/or promote the application of specific service management strategies.

Next, some of the central Radio Resource Management algorithms needed to fully utilize the HCS are described:

- Cell selection,
- Cell reselection,
- Inter-frequency handover

5.1 Cell Selection

Definition 1: Cell selection criterion

The cell selection criterion $S$ is fulfilled when [5]

$$S_{\text{qual}} = Q_{\text{qualmeas}} - Q_{\text{qualmin}} > 0$$  \hspace{1cm} (5.1)

and

$$S_{\text{rxlev}} = Q_{\text{rxlevmeas}} - Q_{\text{rxlevmin}} - P_{\text{compensation}} > 0$$  \hspace{1cm} (5.2)

where

$S_{\text{qual}}$ is the cell selection quality value (dB),

$S_{\text{rxlev}}$ is cell selection Rx level value (dB),
Parameter $P_{\text{compensation}}$ is calculated as

$$P_{\text{compensation}} = \max(UE_{\text{TXPWR MAX RACH}} - P_{\text{MAX}}, 0)$$ (5.3)

where $P_{\text{MAX}}$ is the maximum RF output power of the mobile (dBm) and $UE_{\text{TXPWR MAX RACH}}$ is the maximum transmit power (dBm) the mobile may use when accessing the cell on RACH. The value for $UE_{\text{TXPWR MAX RACH}}$ is broadcasted in system information. Hence, $P_{\text{compensation}}$ is a compensation value for the mobile that cannot transmit at the maximum allowed power on the RACH in the cells. The cell will 'shrink' for those mobiles.

**Definition 2: Suitable cell**

A suitable cell is a cell which the mobile may camp on to obtain normal service. Such a cell shall fulfill all the following requirements [5]:

- The cell is a part of the selected PLMN.
- The cell is not barred.
- The cell is not part of a forbidden registration area.
- The cell selection criteria are fulfilled.

### 5.1.1 Cell Selection in Idle Mode

When the mobile has selected the PLMN to use, it shall create a candidate list of possible cells to camp on. The list can be created with either 'Initial Cell Selection' or 'Stored Information Cell Selection' [5].

**Initial Cell Selection**

This procedure requires no prior knowledge of which RF channels are UTRA carriers. The mobile shall scan all RF channels in the UTRA band to find a suitable cell. On each carrier, the mobile searches first for the strongest cell and reads its system information, in order to find out which PLMN the cell belongs to. If the selected PLMN is found, the search of the rest of carriers may be stopped. Once the mobile has found a suitable cell (see Definition 1) for the selected PLMN, the mobile shall select it.

**Stored Information Cell Selection**

This procedure requires stored information of carrier frequencies and optionally also information on cell parameters, e.g. scrambling codes, from previously received measurement control information elements. Once the mobile has found a suitable cell
(see Definition 1) for the selected PLMN the mobile shall select it. If no suitable cell of
the selected PLMN is found the Initial Cell Selection procedure shall be started.

Thus, the initially selected cell is the strongest suitable cell that has been found within a
frequency band belonging to an allowed PLMN. When a suitable cell has been found,
the mobile shall perform necessary NAS registration procedures. When the mobile has
registered successfully, it shall camp on the cell (state Camped Normally). In this state,
the mobile shall monitor paging information, monitor system information and perform
radio measurements. The measurements shall be used in evaluation of the cell
reselection criteria. The network controls what the mobile shall measure by sending
measurement control information in the system information.

5.2 CELL RESELECTION

5.2.1 Cell Reselection in Idle Mode

After the mobile has found one suitable cell for the selected PLMN, it shall create a
candidate list consisting of the selected cell and its neighboring cells, as received in the
measurement control information via the selected cell.

When the mobile triggers a cell reselection evaluation process (at certain time intervals),
the mobile shall perform ranking of neighboring cells that fulfill the cell reselection
criteria.

Definition 3: Cell Reselection Criteria

When judging for the need of cell reselection, the following two reselection criteria are
applied [5]: Firstly, the quality level threshold criterion \( H \) for hierarchical cell structures
is used to determine whether prioritized ranking according to hierarchical cell re-
seletion rules shall apply, and is defined as

\[
H_s = Q_{\text{meas},s} - Q_{\text{hcs},s} \\
H_n = Q_{\text{meas},n} - Q_{\text{hcs},n} - TO_n \cdot L_n
\]  

for the serving and neighboring cell, respectively. If it is indicated in system
information that HCS is not used, the quality level threshold criterion \( H \) is not applied.

Secondly, the cell ranking \( R \) is defined as

\[
R_s = Q_{\text{meas},s} - Q_{\text{hyst},s} \\
R_n = Q_{\text{meas},n} - Q_{\text{offset},n} - TO_n \cdot (1 - L_n)
\]  

In the equations above:

- \( Q_{\text{meas}} \) is the quality of the received signal,
- \( Q_{\text{hcs}} \) is the quality threshold level for applying prioritized hierarchical
cell reselection,
- \( Q_{\text{hyst}} \) is the hysteresis value. Can be used to “expand” the cell borders.
of the serving cell to achieve a hysteresis effect and to avoid ping-pong effects. The offset between two cells. Can be used to move the cell border between two cells.

Furthermore, in the equations above

\[
T_{On} = \text{TEMPORARY\_OFFSET}_n \cdot W(PENALTY\_TIME_n - T_n)
\]

\[
L_n = \begin{cases} 
0 & \text{if } \text{HCS\_PRIO}_n = \text{HCS\_PRIO}_s \\
1 & \text{if } \text{HCS\_PRIO}_n \neq \text{HCS\_PRIO}_s
\end{cases}
\]

\[
W(x) = \begin{cases} 
0 & \text{for } x < 0 \\
1 & \text{for } x \geq 0
\end{cases}
\]

Parameter \text{TEMPORARY\_OFFSET}_n applies an offset to the \text{H} and \text{R} criteria for the duration of \text{PENALTY\_TIME}_n after a timer \text{T}_n has started for that neighboring cell. One should note that \text{TEMPORARY\_OFFSET}_n and \text{PENALTY\_TIME}_n are only applicable if the usage of HCS is indicated in system information.

The quality value of the received signal, \(Q_{\text{meas}}\), is derived either from the averaged CPICH \(E_c/N_0\) or the CPICH RSCP. The measurement that is used to derive the quality value is set by the ‘Cell_selection_and_reselection_quality_measure’ in system information. Depending on the applied quality measurement, different parameter values are signaled in the system information broadcasts, see Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CPICH RSCP</th>
<th>CPICH (E_c/N_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_{\text{offset,}s,n})</td>
<td>(Q_{\text{offset1,}s,n})</td>
<td>(Q_{\text{offset2,}s,n})</td>
</tr>
<tr>
<td>(Q_{\text{hyst,s}})</td>
<td>(Q_{\text{hyst1,s}})</td>
<td>(Q_{\text{hyst2,s}})</td>
</tr>
<tr>
<td>\text{TEMPORARY_OFFSET}_n</td>
<td>\text{TEMPORARY_OFFSET1}_n</td>
<td>\text{TEMPORARY_OFFSET2}_n</td>
</tr>
</tbody>
</table>

The timer \(T_n\) is implemented for each neighboring cell. The timer \(T_n\) shall be started from zero when one of the following conditions becomes true:

- if \(\text{HCS\_PRIO}_n \neq \text{HCS\_PRIO}_s\) and \(Q_{\text{meas,}n} > Q_{\text{hyst,}n}\)

Or

- if \(\text{HCS\_PRIO}_n = \text{HCS\_PRIO}_s\) and \(Q_{\text{meas,}n} > Q_{\text{meas,}s} + Q_{\text{offset,}s,n}\)

Timer \(T_n\) for the associated neighbor cell shall be stopped as soon as any of the above conditions are no longer fulfilled. Any value calculated for \(T_{On}\) is valid only if the associated timer \(T_n\) is still running. Otherwise, \(T_{On}\) shall be set to zero.
At cell reselection, a timer $T_n$ is stopped only if the corresponding cell is not a neighbor cell of the new serving cell, or if the criteria given above for starting timer $T_n$ for the corresponding cell is no longer fulfilled with the parameters of the new serving cell. On cell reselection, timer $T_n$ shall be continued to be run for the corresponding cells but the criteria given above shall be evaluated with parameters broadcast in the new serving cell if the corresponding cells are neighbors of the new serving cell.

The mobile shall perform ranking of all cells that fulfill the cell selection criterion $S$ among:

- All cells that have the highest $HCS\_PRIO$ among those cells that fulfill the criterion $H \geq 0$. Note that this rule is not valid when UE high-mobility is detected (see Chapter 5.2.3).

- All cells, not considering HCS priority levels, if no cell fulfill the criterion $H \geq 0$. This case is also valid when it is indicated in system information that HCS is not used, that is when serving cell does not belong to a hierarchical cell structure.

The cells shall be ranked according to the $R$ criteria specified above, deriving $Q_{\text{meas,n}}$ and $Q_{\text{meas,s}}$, and calculating the $R$ values using either CPICH RSCP or CPICH $E_c/N_0$ measurements. Finally, the best ranked cell is the one with the highest $R$ value, and the mobile shall perform cell reselection to that cell. In all cases, the mobile shall reselect the new cell, only if the following conditions are met:

- The new cell is better ranked than the serving cell during a time interval $T_{\text{reselection}}$.
- More than 1 second has elapsed since the mobile camped on the current serving cell.

### 5.2.2 Measurement Rules for Cell Reselection when HCS is not Used

If the system information broadcast in the serving cell indicates that HCS is not used, then for intra-frequency and inter-frequency measurements and inter-RAT measurements, the mobiles shall use $S_{\text{qual}}$ for FDD cells and $S_{\text{rlev}}$ for TDD for $S_c$ and apply the following rules [5]:

1. If $S_c > S_{\text{intra\_search}}$, the mobiles need not perform intra-frequency measurements. If $S_c \leq S_{\text{intra\_search}}$, perform intra-frequency measurements. If $S_{\text{intra\_search}}$ is not sent for serving cell, perform intra-frequency measurements.

2. If $S_c > S_{\text{inter\_search}}$, the mobiles need not perform inter-frequency measurements. If $S_c \leq S_{\text{inter\_search}}$, perform inter-frequency measurements. If $S_{\text{inter\_search}}$ is not sent for serving cell, perform inter-frequency measurements.

3. If $S_c > S_{\text{search\_RAT\_m}}$, the mobiles need not perform measurements on cells of RAT $m$. If $S_c \leq S_{\text{search\_RAT\_m}}$, perform measurements on cells of RAT $m$. If $S_{\text{search\_RAT\_m}}$ is not sent for serving cell, perform measurements on cells of RAT $m$.

If HCS is not used and if $S_{\text{limit\_Search\_RAT\_m}}$ is sent for serving cell, UE shall ignore it.

### 5.2.3 Measurement Rules for Cell Reselection when HCS is Used

Assuming that system information broadcast in the serving cell indicates that HCS is used, inter-frequency cell reselection measurements are triggered when the $S_{\text{rlev}}$ of the
serving cell drops below the threshold $S_{\text{searchHCS}}$ or when the $S_{\text{qual}}$ of the serving cell drops below the threshold $S_{\text{intersearch}}$. Furthermore, if these parameters are not set in the system information the mobile has to measure all inter-frequency cells all the time [5].

A special HCS priority ($HCS\_PRIO$) can be defined for the serving and the neighboring cells. If there are cells in the neighbor list with higher $HCS\_PRIO$ than the serving cell, these cells are measured all the time. With these priorities it is possible to force the mobiles to camp to micro layer whenever it is available. This approach makes sure, together with inter-frequency handovers, that the micro layer can be fully utilized.

Users with high mobile speeds can be directed from micro to macro layer already in idle mode: If the number of cell reselections during time period $T_{CR_{max}}$ exceeds $N_{CR}$, high mobility has been detected. During this high mobility state, the mobile will perform cell reselection measurements on all intra- and inter-frequency cells, which have a lower HCS priority level than the serving cell. Furthermore, it will prioritize the reselection of intra- and inter-frequency neighboring cells on a lower HCS priority level before the neighboring cells on the same HCS priority level [5].

### 5.2.4 Cell Reselection when Leaving Connected Mode

When returning to idle mode from connected mode, the mobile shall select a suitable cell to camp on. Candidate cells for this selection are the cell(s) used immediately before leaving connected mode. If no suitable cell is found, the mobile shall use the Stored Information Cell Selection procedure in order to find a suitable cell to camp on.

When returning to idle mode after an emergency call on any PLMN, the mobile shall select an acceptable cell to camp on. Candidate cells for this selection are the cell(s) used immediately before leaving connected mode. If no acceptable cell is found, the mobile shall continue to search for an acceptable cell of any PLMN in state Any Cell Selection.

### 5.3 Inter-Frequency Handover

Cell Selection process aims at finding a cell for the mobile to camp on, when it is returning from “out of coverage” or when it is switched on. Furthermore, the purpose of Cell Reselection procedure is to make the mobile to camp on a cell, which provides sufficient quality in terms of CPICH $E_c/N_0$ and/or CPICH RSCP, even if this is not the optimal cell all the time. Hence, by applying the idle mode control with the usage of HCS parameters the mobile can be made to camp to micro cell whenever it is available.

While in $Cell\_DCH$ state intra-frequency and inter-frequency handover algorithms are required to support user mobility. A number of inter-frequency handover scenarios can be highlighted, see Figure 11. These different scenarios are discussed in the next chapters.

The downside of the inter-frequency handover is that it is a “hard” handover, i.e. not seamless. Furthermore, in order to be able to perform inter-frequency measurements, the mobile must enter into a compressed mode transmission, which results in reduced quality. The compressed mode is discussed further in Chapter 5.3.3.
5.3.1 Inter-Frequency Handover Based on Coverage

Two types of coverage-based inter-frequency handover scenarios can be highlighted:

1. Mobile connected to a micro cell moves out of micro layer coverage area. A coverage-based inter-frequency handover from micro to macro layer is required, see Figure 12.

2. Mobile connected to a macro cell moves into a micro layer coverage area. Due to the adjacent channel interference the macro cell downlink coverage area might be shrunk (see [3]), and eventually, a coverage-based inter-frequency handover from macro to micro (or second macro) layer is required, see Figure 13.
The coverage-based inter-frequency measurements and handovers are typically triggered by the transmitted power levels and the link quality measurements in the following way:

- **Uplink:** Mobile transmission power reported to RNC (triggered e.g. by the UE internal measurement event 6a, “The UE Tx power becomes larger than an absolute threshold”, or event 6d, “The UE Tx power reaches maximum value” [6]) or uplink quality obtained from the outer loop power control.

- **Downlink:** Transmitted code power reported from the base station to RNC or the downlink quality (e.g. CPICH $E_c/N_0$) reported by the mobile

As an example, assume that the macro layer consists of $B_M$ base stations and the micro layer consists of $B_u$ base stations, the CPICH $E_c/N_0$ for base station $b$ measured by mobile $m$ can be expressed as

$$\frac{E_c}{N_0}\bigg|_{m,b} = \frac{P_{CPICH,b} G_{m,b}}{N_m} + \sum_{k=1}^{B_M} \frac{P_{tot,k} G_{m,k}}{ACIR_{m,k}} + \sum_{n=1}^{B_u} \frac{P_{tot,n} G_{m,n}}{ACIR_{m,n}}$$

(5.6)

where

- $P_{CPICH,b}$ is the CPICH transmit power,
- $G_{m,b}$ is the path gain between mobile $m$ and base station $b$,
- $N_m$ is the noise power of mobile $m$,
- $P_{tot,k}$ is the total output power of base station $k$,
- $ACIR_{m,k}$ is the Adjacent Channel Interference power Ratio between mobile $m$ and base station $k$.

Alternatively, the triggering can be based on transmitted downlink code power $P_{m,b}$, which can be modeled as
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\[
P_{m,b} = \rho_{m,b} \left( N_m + \sum_{k=1}^{K_{m,b}} P_{tot,k}G_{m,k} + \sum_{n=1}^{N_{m,b}} P_{tot,n}G_{m,n} \frac{ACIR_{m,k}}{G_{m,b}} - (1 - \alpha_{m,b})P_{tot,b} \right)
\]

where \( \rho_{m,b} \) is the required CIR for mobile \( m \) connected to base station \( b \),
\( \alpha_{m,b} \) is the downlink orthogonality factor for mobile \( m \) connected to base station \( b \) (\( \alpha = 0 \) means perfect orthogonality).

5.3.2 Inter-Frequency Handover Based on Mobile Speed and System Load

If fast moving mobiles are connected to small micro cells, the amount of signaling related to e.g. handovers can be considerable. Furthermore, due to the signaling and processing delays, resulting in handover delay, the uplink interference can increase, or the downlink can be lost. Therefore, fast moving mobiles located within the micro layer coverage area should be handed over from micro to macro layer, see Figure 14. The high user mobility can be detected e.g. by looking at the frequency of the active set updates.

In case of HCS solution, the cells are organized in layers with different priority levels according to the spectral efficiency each layer can provide; the highest priority level being allocated to the layer that ensures the best spectral efficiency (e.g. micro layer). Normally, traffic is initially directed to the highest priority layer available so that the total capacity per unit area is maximized. However, due to e.g. user mobility, load sharing between the layers may be needed.

Since the micro layer can provide a higher spectrum efficiency than the macro layer, a proper goal would be to aim at full utilization of the micro layer, where applicable. Furthermore, the loading between the layers should be balanced before inter-system handovers are initiated.

The traffic steering function taking care of the overflow of traffic between the layers may be invoked e.g. at every call set-up, or only when the target cell is lacking resources for a new call or soft handover leg. In the latter case, the mobile can be...
overflowed to the alternative layer, if applicable. Otherwise, the call/leg can be admitted in the target cell, only if the required amount of radio resources can be released first. Typically, the resources can be released by triggering overflow (i.e. inter-frequency handover) of mobiles having a service or mobility profile suitable for the other layer. In certain cases, dropping may be needed to enforce a specific service management strategy, e.g. to give priority to a high demanding service over a low priority one. In [7] a policy has been proposed, which aims at ensuring fair access among different service classes and protecting intra-layer handover traffic in the presence of complete resource sharing among various services. Overload in the micro layer is managed by forcing narrow bandwidth calls to be handed over to the macro layer or dropped, in order to serve handover and/or new call requests of a wider bandwidth class. The analysis points out that unfairness among services can be reduced without resorting to resource partition, thus avoiding trunking inefficiency.

As for the trade-off between capacity and signaling load, the use of a threshold velocity at call set-up determines the portions of the total traffic, which will be offered to different hierarchical layers. The assessment of the threshold velocity is an optimization issue, where the goal is to minimize the handover rate while keeping the GoS above an acceptable level. If this optimization problem is solved during the network planning process, the optimal threshold will be obtained assuming a certain traffic and mobility parameters. Unfortunately, the characteristics of a system in operation are changing dynamically. Therefore, [8] proposes a method for a dynamical adaptation of the threshold velocity, based on the above-mentioned optimization goal. As a result, the threshold is modified according to the changes in the traffic load and the mobility properties of the mobiles.

5.3.3 Inter-Frequency Measurements with Compressed Mode

WCDMA uses continuous transmission and reception and can not make inter-frequency measurements with single receiver if there are no gaps generated to the WCDMA signals. Therefore, a method called compressed mode is needed for both inter-frequency and inter-system measurements. The compressed mode means that transmission and reception are halted for a short time in order to perform measurements on the other frequencies, see Figure 15. The intention is not to lose any data but to compress the data transmission in the time domain. The standard proposes three possibilities for the transmission time reduction [9]:

- Puncturing. A number of bits of the coded data are simply discarded, resulting in a lower performance of the coding. In practice, this method is limited to rather short Transmission Gap Lengths, since the puncturing has some practical limits. The benefit is that the existing spreading factor is kept and therefore no new requirements are caused for the channelisation code usage.

- Increasing the data rate by reducing the spreading factor by 2. This method is suitable also for longer Transmission Gap Lengths.

- Higher layer scheduling. Higher layers set restrictions so that only a subset of the allowed Transport Format Combinations are used in a compressed frame. The maximum number of bits that will be delivered to the physical layer during the compressed radio frame is then known and a transmission gap can be generated.
Since more power is needed during the compressed mode, the use of compressed mode will affect the WCDMA coverage. Furthermore, since the fast power control loop is not active during the silent period, and the effect of interleaving is decreased, a higher $E_b/N_0$ target is required, which affects the WCDMA capacity.

Due to the impact on WCDMA capacity and coverage, the compressed mode should be activated by the RNC only when there is a real need to execute an inter-system or inter-frequency handover. This can be done for example by monitoring the downlink transmission powers for each user, or with the help of mobile measurements.

As an example, the triggering of compressed mode can be based on the inter-frequency reporting events 2d and 2f [6]:

- **Event 2d.** The estimated quality of the currently used frequency is below a certain threshold. As a result of this event, inter-frequency measurements are initiated.
- **Event 2f.** The estimated quality of the currently used frequency is above a certain threshold. As a result of this event, inter-frequency measurements are terminated if they were initiated for mobility reasons.

### 5.3.3.1 Parameterisation of the Compressed Mode

A transmission gap pattern sequence consists of alternating transmission gap patterns 1 and 2. Furthermore, each of these patterns in turn consists of one or two transmission gaps, see Figure 16. The following parameters are used to characterize a transmission gap pattern [10]:

- **TGSN (Transmission Gap Starting Slot Number):** A transmission gap pattern begins in a radio frame, henceforward called first radio frame of the transmission gap pattern, containing at least one transmission gap slot. TGSN is the slot number of the first transmission gap slot within the first radio frame of the transmission gap pattern.
- **TGL1 (Transmission Gap Length 1):** This is the duration of the first transmission gap within the transmission gap pattern, expressed in number of slots.
- **TGL2 (Transmission Gap Length 2):** This is the duration of the second transmission gap within the transmission gap pattern, expressed in number of slots. If this parameter is not explicitly set by higher layers, then TGL2 = TGL1.
- **TGD (Transmission Gap start Distance):** This is the duration between the starting slots of two consecutive transmission gaps within a transmission gap pattern, expressed in number of slots. The resulting position of the second transmission gap within its radio frame(s) shall comply with the limitations of [9]. If this parameter is
not set by higher layers, then there is only one transmission gap in the transmission gap pattern.

- **TGPL1 (Transmission Gap Pattern Length):** This is the duration of transmission gap pattern 1, expressed in number of frames.

- **TGPL2 (Transmission Gap Pattern Length):** This is the duration of transmission gap pattern 2, expressed in number of frames. If this parameter is not explicitly set by higher layers, then TGPL2 = TGPL1.

The following parameters control the transmission gap pattern sequence start and repetition:

- **TGPRC (Transmission Gap Pattern Repetition Count):** This is the number of transmission gap patterns within the transmission gap pattern sequence.

- **TGCFN (Transmission Gap Connection Frame Number):** This is the CFN of the first radio frame of the first pattern 1 within the transmission gap pattern sequence.

![Figure 16. Illustration of compressed mode pattern parameters.](image)

### 6 SUMMARY

In this paper a brief overview of the hierarchical cell structures has been given. Typically, in limited urban areas, where the capacity need is especially high, and site acquisition is particularly difficult, network deployment based on hierarchical cell structures (macro, micro, pico) becomes an attractive solution. The different cell layers are characterized by features like carrier frequency, cell size, output power and antenna location.

The hierarchical cell structure enables an efficient and flexible handling of traffic with different characteristics in terms of service and mobility. However, in order to achieve
this, the radio network planning process has to be efficient enough to obtain full connectivity between cells belonging to different layers, while maximizing the total system capacity. A task, which is often easier said than done.

7 REFERENCES


HOME EXERCISE

Assuming a simple one-directional approach, calculate the diameter of the microcell downlink service area, i.e. the value for $R$, see the Figure below. Thus, here the service area includes also the soft handover zones.

Consider two scenarios:

**Scenario 1**: Distance between macro and micro base station $D = 500$ m

**Scenario 2**: $D = 1500$ m

Assume the following parameter values:

- $P_{CPICH,M} = 32$ dBm
- $P_{CPICH,\mu} = 22$ dBm
- $G_M = 15$ dBi
- $G_\mu = 5$ dBi
- $G_{UE} = 0$ dBi
- $A_M = 20.0$ dB (assuming that the unit for $d_M$ is [m])
- $\alpha_M = 4.0$
- $A_\mu = 28.0$ dB (assuming that the unit for $d_\mu$ is [m])
- $\alpha_\mu = 4.0$

Furthermore, the size of the soft handover window is 3 dB. Finally, ignore the impact of log-normal fading.