Final Report

“Radio Frequency Spectrum Requirement Calculations for Future Aeronautical Mobile(Route) System. AM(R)S”

TRS-125/02

Version 1.1

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<td>Limitations of PIAC Method, missing Ground Communication and “Data Explosion” Phenomena</td>
<td>8</td>
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<td>Remark regarding Safety of Live Application</td>
<td>8,30,41</td>
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<td>Clarification: Impact of non homogenous Aircraft Distribution</td>
<td>16,33</td>
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<td></td>
<td>Calculation of Bandwidth without Video Service</td>
<td>37</td>
</tr>
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<td></td>
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<td>Differences between ITU – Method and used Approach</td>
<td>38 ff.</td>
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<td>Clarification: Maximum Transmit Power for Base Station / 50 km Cell Radius</td>
<td>16,32</td>
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<td></td>
<td></td>
<td></td>
<td>Clarification: Selection of Eb/No Requirement</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Comparison of Net System Capabilities for different systems</td>
<td>40</td>
</tr>
</tbody>
</table>
# Table of Content

1. **EXECUTIVE SUMMARY** .................................................................................................................. 5  
   1.1. **GENERAL** ................................................................................................................................. 5  
   1.2. **SUMMARY OF RESULTS** ........................................................................................................ 5  

2. **VERIFICATION OF EXISTING EUROCONTROL MODEL** ................................................................. 7  
   2.1. **DISCUSSION OF THE METHOD TO CALCULATE THE EXPECTED THROUGHPUT** ................. 7  
   2.1.1. Calculation of the average Number of Aircraft ........................................................................ 7  
   2.1.2. Calculation of the required Bandwidth for the different Services ............................................... 8  
   2.2. **DISCUSSION OF CALCULATIONS OF REQUIRED BANDWIDTH** ............................................. 8  
   2.2.1. Analysis of the Calculations in the Link Budget ....................................................................... 9  
   2.2.2. Analysis of Method to Calculate C/N0 at Cell Border ............................................................. 13  
   2.2.3. Discussion of the used Assumptions during Calculation ......................................................... 15  

3. **SENSITIVITY ANALYSIS** ............................................................................................................... 18  
   3.1. **IMPROVED MODEL FOR BANDWIDTH CALCULATION** .......................................................... 18  
   3.1.1. General Equation for the required Bandwidth ......................................................................... 18  
   3.1.2. Impact of fixed RF-Bandwidth ................................................................................................. 20  
   3.2. **RESULTS OF SENSITIVITY ANALYSIS** .................................................................................... 21  
   3.2.1. Variation of Cell Radius ......................................................................................................... 22  
   3.2.2. Variation of Transmit Power .................................................................................................. 23  
   3.2.3. Variation of Adjacent Cell Factor ........................................................................................... 25  
   3.2.4. Variation of Eb/No Requirement ............................................................................................ 27  
   3.2.5. Variation of Frequency ........................................................................................................... 28  

4. **CALCULATION OF REQUIRED BANDWIDTH** ................................................................................ 30  
   4.1. **CALCULATION OF THROUGHPUT PER SERVICE AND AIRCRAFT** ...................................... 30  
   4.2. **SYSTEM PARAMETER USED FOR CALCULATION** .................................................................. 32  
   4.3. **REQUIRED BANDWIDTH FOR VOICE** ..................................................................................... 33  
   4.4. **REQUIRED BANDWIDTH FOR DATA AND SECURITY** .............................................................. 34  
   4.5. **REQUIRED BANDWIDTH FOR COMMERCIAL DATA** ............................................................. 34  
   4.6. **REQUIRED BANDWIDTH FOR VIDEO** .................................................................................... 35  
   4.7. **REQUIRED BANDWIDTH FOR AVERAGED DATA RATE** ......................................................... 35  
   4.8. **TOTAL BANDWIDTH REQUIREMENT** ...................................................................................... 36  
   4.9. **COMPARISON OF USED METHODOLOGY WITH METHODOLOGY DEFINED BY ITU** ............ 38

© LS telcom AG reserves all rights including intellectual property rights and all rights of disposal
4.9.1. Comparison of Net System Capabilities ................................................................. 40

5. CONCLUSION ................................................................................................................. 41

6. APPENDIX .................................................................................................................... 42
   6.1. REFERENCES ............................................................................................................ 42
   6.2. MOTIVATION FOR MULTI RATE MODEL ............................................................. 44
   6.3. USED PARAMETER FOR THROUGHPUT CALCULATION .................................... 47
   6.4. MATHEMATICAL CONVENTIONS ........................................................................ 51
   6.5. CALCULATION OF C/NO FROM C/I0 AND C/N0 .............................................. 52
   6.6. CALCULATION OF B BASED ON C/I0 REQUIRED AND U ................................. 53
   6.7. MODELING OF FACTOR FOR ADJACENT CELL INTERFERENCE ...................... 54
   6.8. GENERAL EQUATION FOR THE CALCULATION OF THE REQUIRED BANDWIDTH B ......................................................................................................................... 56
   6.9. IMPACT OF SPREADING FACTOR ........................................................................... 58
   6.10. SAMPLE CALCULATION OF INTERFERENCE SITUATION FOR CELL WITH TWO SERVICES........................................................................................................ 60
1. Executive Summary

1.1. General

The availability of radio spectrum is vital for efficient air traffic management and its safety of life services. Failure to be able to meet the demand for radio spectrum will prevent the full implementation of the ECAC ATM2000+ strategy. Therefore the air traffic capacity will not be adapted to the future traffic, causing increased delays. The ATM 2000+ strategy recognizes that the development of communication data links and the use of more spectrally efficient technology are important factors to solve the foreseen communication capacity limitation. The ICAO AMCP and EUROCONTROL COMT have decided to request ITU to provide a new radio allocation for these new communication applications.

For this purpose EUROCONTROL is preparing a number of documents for submissions into the CEPT and the ITU. Aviation is hoping to secure an agenda item for WRC 2006 to open discussions for a new radio spectrum allocation for an Aviation Mobile Communication system.

In this context it has been necessary to investigate some preliminary scenarios and carry out provisional calculations as to the amount of spectrum required. To do this, EUROCONTROL has developed a preliminary spectrum capacity model working on basic fundamentals.

The scope of this study has been to validate the general feasibility of the method and the taken assumptions during development of the model by EUROCONTROL, to extend the model and to perform provisional bandwidth calculations.

At the current stage of the project a decision regarding the technology has not been taken, the calculations have been performed for an exemplary state of the art W-CDMA system like it is used in 3G cellular Networks. System parameter have been selected in accordance with current standards, and the impact on bandwidth requirement has been analyzed by the means of a sensitivity analysis.

The required bandwidth has been determined for different services like voice, data and video separately and the total bandwidth requirements have been calculated.

1.2. Summary of Results

The method used to calculate the expected throughput in [1] is based on what is done for terrestrial cellular networks like UMTS or IMT-2000 by the ITU ([12] and [10]) and the UMTS Forum [11]. One major difference is that in [10] and [11] the required bandwidth is calculated sepa-
rately and finally summed up over the different services like speech and data while the used approach in [1] first sums up the data rates of all services and than calculates the required bandwidth. Though the general method to calculate the bit rates per service is applied in a correct way some factors increasing the bit rates like coding, protocol overhead and impact of handover are missing or are handled in different ways for the diverse services like voice and data.

The method used to calculate the required bandwidth is based on principle equations for a CDMA System and are valid under several assumptions like ideal working power control, large number of aircraft with homogenous spatial distribution and equal data rate per aircraft. Whereas the imprecision coming from most of the assumptions can be justified or removed by slight changes in the model, the latter one is a strong limitation to the method because the projected system will use different data rates in parallel. It is not yet known how this different data rates will be transmitted on the air interface in the new system, but it is possible that a similar method like in 3G-CDMA-Systems will be used. If under this scenario the applied method to calculate the required bandwidth will be exact enough should be topic of further investigations.

The preliminary model developed by EUROCONTROL has been extended by DFS / LS telcom. The extension comprises a more general modeling of the bandwidth calculation and the consideration of systems that are using a fixed RF-Bandwidth. The calculation of throughput information for different services has been implemented in an excel sheet and the general handling of the excel module has been improved.

With the extended model a sensitivity analysis has been performed to identify the impact of technical parameter of the bandwidth requirements. Based on the results of this analysis the parameter for the bandwidth calculation has been selected.

At the final stage of the project the bandwidth requirement has been calculated. For this the traffic in the airspace sector has been modeled in two different ways. The one way follows the method outlined by EUROCONTROL in [1] where an average data rate per aircraft is calculated. The other way has been to calculate channel requirements and use fixed channel rates to obtain the final bandwidth. For the latter one, additional calculations have been performed for a system with fixed RF-Bandwidth (3,84 Mchip/s and 1,2288 Mchip/s).

Depending on the calculation method the bandwidth requirements are found to be in a range of approx. 16 to 22 MHz. (4 to 8 MHz for Uplink (ground to aircraft) and 12 to 14 MHz for Downlink (aircraft to ground)). When video services are not considered the bandwidth requirements are reduced to a range of 10 to 20 MHz.

As the results have been obtained disregarding the impact of inter service interferences further studies should examine this effect to consolidate the found results.
2. Verification of existing EUROCONTROL Model

This section discusses the calculations used in [1] to determine the required bandwidth for a future ground based cellular network for Aeronautical Mobile (Route) System AM(R)S. There has been no decision taken yet regarding the technology that may be used for this system. The provisional calculations [1] have been performed under the assumption that state of the art CDMA-technology will be used.

The calculations are done in two parts that are:

- Calculation of the expected throughput in kBit/s
- Calculation of the required bandwidth to satisfy expected throughput

The two calculation methods will be discussed separately in the following sections.

2.1. Discussion of the Method to calculate the expected Throughput

The calculation of the required capacity is done in the following steps:

- Calculation of the average number of aircraft in one airspace sector for the year 2029 which is expected to be the year when the new system will be replaced
- Determination of bit rate for different services like voice, data, and, video for uplink and downlink
- Summation over all services to get the complete throughput

2.1.1. Calculation of the average Number of Aircraft

The calculation for the average number of aircraft in one airspace sector is done in a straightforward way. Based on the PIAC calculated for year 2000 the PIAC for 2029 should be calculated. In fact the PIAC for 2030 has been calculated and used for the ongoing analyses of traffic.

Under the assumption that the aircraft are distributed homogenous in the complete area of the airspace sector the PIAC may be distributed by the size of the sector. This will lead to the aircraft density per km² that is quite similar to user densities used for the traffic dimensioning of mobile networks. Nevertheless one limitation for the homogenous distribution may occur, when the cell areas of the projected network will get smaller and smaller. The one sector that contains
the airport will be loaded higher than the other ones because all aircraft will cross this sector during start and landing.

As on the one hand the forecast based on PIAC does not include traffic needed for taxiway and ground communication, the cell load at the airport cell will be higher than assumed in the used approach. On the other hand an umbrella cell for transiting aircraft may serve a part of the traffic and therefore decrease the traffic load in the network.

A constant traffic demand per aircraft for the complete period (year 2000 to 2030) has been used. A growth in offered traffic per aircraft based on the implementation of new services has not been respected.

For calculations in further studies therefore the model used for the traffic forecast should be extended.

2.1.2. Calculation of the required Bandwidth for the different Services

The calculation of the required bandwidth is done for different services and based on statistical information and assumptions coming from existing applications. For each service the needed average bit rate is calculated and afterwards the total data rate is obtained by summing up over all services. For some services additional factors like protocol overhead and overhead for handover are respected whereas for other services these factors have not been applied. It seems that no factor for the overhead coming from channel coding has been used. In fact it is very probable that coding will be used and therefore the gross bit rates on the air interface will be higher that the data rates offered to the end user. Additionally an overhead for the control information used inside the system itself (e.g. for handover and power control) should be added.

In our opinion the effect of soft handover on the required bandwidth should not be modeled inside the calculation of the required data rate for services but should be implemented in the calculation of number of aircraft per cell. This will be in accordance to the fact that soft handover will increase the number of aircraft in a cell but not the data rate used per aircraft.

The calculation for voice is based on the average talk time, the time spent in the sector, and from the PIAC value for 2030. From this the average number of needed channels (at 20 kBit/s) is calculated. This method does not care about blocking characteristics. At the first glance, this is uncommon to the dimensioning of telecommunication networks, where typically a blocking model like Erlang B is applied for voice services. Nevertheless this approach can be justified because the safety-of-life applications in aviation do not allow blocking.

2.2. Discussion of Calculations of required Bandwidth

In this paragraph the calculations performed in the file link budgetmodelversion3.xls will be analyzed. The discussion will be done in the following steps
• Analysis of the calculations performed in the link budget sheet
• Analysis of used method to calculate C/Nto at the cell border
• Discussion of the used assumptions during calculation

2.2.1. Analysis of the Calculations in the Link Budget

The Excel-File linkbudgetmodelversion3.xls contains 3 sheets (Feuil1, Feuil2 and Feuil3). In the following only Feuil1 and Feuil3 are discussed. Feuil3 contains the same link budgets for different cell radius as in document [1] whereas Feuil 1 contains two link budgets. The first link budget is the same as found in [2] for a data rate of 384 kBit/s the second seems to be an intermediate step towards the budgets on Feuil3.

The calculations in the spreadsheets are based on some principal equations as found in literature.

For the calculation of the required carrier to noise ratio in the case of digital transmission the following equation applies:

\[
\frac{C}{N_o} \text{required} = \frac{E_b}{N_o} \text{required} + 10 \log r \quad [\text{dBHz}]
\]

Equation (2-1) can be found for example in [6].

The following definitions apply:

\[
\frac{E_b}{N_o} \text{required} \quad \text{Required energy per bit to noise ratio for a given modulation scheme and a given bit error rate for the transmission. In some definitions (for example for ETSI UMTS) this value also includes the gain coming from error correction methods like interleaving and coding.}
\]

\[
r \quad \text{Gross bit rate of the signal including overhead coming from error protection and transmission protocol}
\]

\[
C = 10 \log( c) \quad \text{Received power of wanted signal in dBW}
\]

\[
N_o = 10 \log( n_o) \quad \text{Power spectral density of all signals exclusive the wanted signal in dBHz}
\]

For a CDMA system \(N_o\) consists of two parts, the one coming from thermal noise, the other one coming from self-interference:
\[ N_o = 10 \log(n_{so} + i_o) \] [dBHz] \hspace{1cm} \text{(2-2)}

with

\( n_{so} \)  
Power spectral density of thermal noise

\( i_o \)  
Power spectral density of other interference

For calculation of the available carrier to self-interference ratio for a single cell loaded with \( u \) aircraft the following equation is used:

\[ \frac{C}{I_{\text{available}}} = -10 \log u \] [dB] \hspace{1cm} \text{(2-3)}

In fact this is an approximation for \( u \gg 1 \), the correct equation can be obtained under the assumption that all received signals form the different aircraft are having the same power \( c \) in Watt (ideal power control) [5]:

\[ \frac{C}{I_{\text{available}}} = 10 \log \left( \frac{c}{i} \right) = 10 \log \left( \frac{c}{(u - 1) \cdot c} \right) = -10 \log (u - 1) \] [dB] \hspace{1cm} \text{(2-4)}

with

\( c \)  
Power of received signal in watt

\( i \)  
Power of all interfering signals in watt

\( u \)  
Number of aircraft in cell

It is obvious that Equation (2-4) is only valid for \( u > 1 \), as for a system with only one aircraft no self-interference is found under the assumption that interference from multi path propagation can be neglected.

To calculate the required bandwidth that is needed to allow transmission for a given number \( u \) of aircraft in a cell two different approaches are used inside the excel-file.

**Approach used on Feuil1:**

This calculation method is using a straightforward approach to check if a given bandwidth \( b \) is sufficient to operate \( u \) aircraft with a data rate \( r \) in a cell with a specific size:

**Step 1**
The C/No required for a given bit rate \( r \) is calculated using equation (2-1).
Step 2
Under the assumption that the bandwidth $b$ is available and $u$ aircraft are using the system the available C/I in the cell is calculated, based on equation (2-3).

Step 3
To check if the C/No requirement is met in the cell, the available C/No is calculated from the available C/I. For this, first the available C/Io is calculated from the available C/I:

$$\frac{C}{I_i} \text{ available} = 10 \log \left( \frac{c}{i_i} \right) = 10 \log \left( \frac{c}{i f b} \right) = 10 \log (b) - 10 \log \left( \frac{c}{i} \right) = B - \frac{C}{I_i} \text{ available} \quad \text{[dBHz]} (2-5)$$

Afterwards the available C/No is derived from the available C/Io and the C/No:

$$\frac{C}{N_o} \text{ available} = -10 \log (10^{\frac{J_o}{10}} + 10^{\frac{J_{out}}{10}}) \quad \text{[dBHz]} (2-6)$$

with

$c$ Signal power in watt

$n_o$ Spectral power density of thermal noise

The validity of (2-6) is shown in Appendix 6.5.

The calculation of $c/n_o$ is done at the cell border based on system parameter like antenna gain and transmit power (see section 2.2.2 for a discussion of the used method).

Step 4
The required and the available C/No are compared. If the available C/No is higher than the required one, the available bandwidth $b$ is sufficient.

Approach used on Feuil3:

In this approach the required bandwidth $b$ that is needed to operate $u$ aircraft with a data rate $r$ in a cell of a specific size $s$ is calculated. Additional to Feuil1, three further parameter have been added in the spreadsheet: The “Cell Loading Factor” the “Cell Capacity Factor” and the “Aggregate Data Throughput”. The “Cell Loading Factor” is not used in the calculation whereas the “Cell Capacity Factor” is used to model the influence of adjacent cell interference that has been neglected in the calculation on Feuil1. The “Aggregate Data Throughput” is standing for the overall data throughput in the cell. The following steps are used during the calculation:
Step 1
Calculation of the data rate $r$ used by one aircraft in the cell. For this the following equation is used:

$$ r = \frac{V}{u \cdot \gamma} \text{ [bit/s]} \quad (2-7) $$

with

- $u$ Number of aircraft in cell
- $\gamma$ Cell Capacity Factor

$$ \gamma = \frac{\text{Cell Capacity with Adjacent Cell Interference}}{\text{Cell Capacity without Adjacent Cell Interference}} \quad (2-8) $$

$V$ Throughput in bit/s

The consideration of $\gamma$ in equation (2-7) has the effect that the data rate $r$ per user is increased when the adjacent cell interference is getting higher. This is confusing at the first moment because it seems to be logical that $r$ just depends on the overall data throughput and the number of aircraft. In Appendix 6.7 it is shown that under the assumption of $u \cdot c >> n$, this method is valid.

Step 2
Calculation of the required C/No according to Equation (2-1)

Step 3
Calculation of the required C/Io from the required C/No calculated in Step 3. For this the following equation is used.

$$ \frac{C}{Io_{\text{required}}} = -10 \log \left( 10^{\frac{-Io_{\text{required}}}{10}} - 10^{\frac{-Io_{n}}{10}} \right) \text{ [dBHz]} \quad (2-9) $$

The validity of (2-9) can be shown in a similar way like it has been done for Equation(2-6) in Appendix 6.5.

Step 4
In the last step the required bandwidth is calculated using the equation
Equation (2-10) can be derived from Equation (2-3) as shown in Appendix 6.6.

Please note that, like discussed for equation (2-3), equation (2-10) is only valid for $u >> 1$. For small numbers of aircraft the term $\log u$ should be replaced by $\log(u - 1)$.

Finally based on $b$ the bandwidth required for guard bands is calculated by multiplying $b$ with the channel reuse factor. The total spectrum required is then calculated by the following equation:

$$ b_{\text{total}} = \text{channel} - \text{reuse} \cdot factor \cdot b + b \quad \text{[Hz]} \quad (2-11) $$

Based on Equation (2-11) large guard bands will be respected in the total required bandwidth. In [9] the ITU adds 5% of the calculated bandwidth for guard bands.

2.2.2. Analysis of Method to Calculate C/Nto at Cell Border

In the spreadsheet the signal to thermal noise ratio is calculated based on the following system parameters:

- $P_t$ Transmit power in dBW
- $G_t$ Antenna gain of transmit antenna in dBi
- $G_r$ Antenna gain of receive antenna in dBi
- $F_r$ Noise factor of receiver in dB
- $L_{\text{Cable}}$ Cable loss in dB
- $L_{\text{Path}}$ Path loss in dB
- $L_{\text{Pol}}$ Polarization loss in dB
- $k = 1.38 \cdot 10^{-23}$ Boltzman’s constant in Watt/Kelvin
- $T$ System temperature in Kelvin
- $d$ Distance to cell border in km
- $f$ Carrier frequency in MHz
\[ \frac{C}{N_{to}} = P_t + G_t - L_{Path} + G_r - L_{Cable} - L_{Pol} - F_r - 10 \log(kT) \text{ [dBHz]} \] (2-12)

For the calculation of the path loss the free space attenuation and the hygroscopic attenuation are respected. For the free space attenuation the following equation is used. It can be found for example in [4]:

\[ L_{free-space} = 32.4 + 20 \log d + 20 \log f \] (2-13)

The used equation for the hygroscopic loss (Feuil1 in the second link budget) seems not to be correct because the loss will get smaller when distance will increase. Nevertheless this is not very important, as the equation has been again replaced in the budgets in Feuil3, which are the final ones. The equation used in Feuil3 is

\[ L_{hygroscopic} = 0.133 \cdot d \] (2-14)

This equation is matching the shape “ Attenuation = Factor * Distance” as found for example in the recommendations of ITU.

The path loss is then calculated as sum of free space attenuation and hygroscopic attenuation:

\[ L_{Path} = L_{free-space} + L_{hygroscopic} \] (2-15)

Since the path loss depends of the distance \( d \), the calculation of C/Nto is only valid at this position in the cell. In the link budgets for \( d \) the distance to the cell border is used. This is reasonable because this is the point inside the cell where C/Nto will have the smallest value without power control. Under the assumption that ideal power control will be used the system will adjust the power \( c \) to the same value all over the cell and therefore the same C/Nto will be available in the whole cell.

The calculation of the C/Nto doesn’t comprise any margins for fading on the air interface. Again under assumption of ideal fast power control this is valid because power control will equalize the fading notches. In this case a margin for power control headroom should be implemented in the budged allowing some power reserves at the cell border. This will lead to smaller cell areas.
2.2.3. Discussion of the used Assumptions during Calculation

The following assumptions have been used during the calculations. They are either made directly in [1] or are coming from the used equations of the excel file:

- Large number of aircraft
- Perfect power control
- Homogenous distribution of aircraft
- Same data rate for all aircraft

**Large Number of Aircraft**

The assumption that a large number of aircraft is connected in one cell is taken during calculation of the interference in the cell and by respecting the adjacent cell interference in the calculations of Feuil3. During the calculation of self-interference in the cell this assumption can be removed by exchanging the term \( \log(u) \) by \( \log(u-1) \). The latter limitation may be removed by applying a more general equation for the required bandwidth.

**Perfect Power Control**

Ideal power control for uplink and downlink means that the ground station controls all signals in a way, that signals from different sources are received with the same power. This has to be valid for uplink and downlink. It is quite obvious that for the single cell case this can be maintained for the downlink because each aircraft can adjust it’s transmit power separately according to the path loss towards the ground station. Therefore all signals will have the same receiving power \( c \), even if the aircraft are operating in different distances to the ground station. In the uplink, for the operation of the system, no power control is needed because all signals transmitted to the different aircraft in the cell are coming from the same source and are suffering therefore the same path loss. When the same transmit power \( P_t \) is used towards all aircraft, the requirement that all received signals are having the same power \( c \) is fulfilled. Power Control in uplink is only used to minimize the overall transmitted power and therefore to minimize adjacent cell interference.

The general situation will not change when adjacent cell interference has to be respected. Again power control will work as described above, the only difference is, that higher transmit powers will be needed to fulfill the Eb/No requirements.

Ideal power control assumes that there is no limit for the transmit power available to the aircraft. In reality, of course this is not possible. This leads to the effect that the possible cell sizes will get smaller when interference in the cell increases. This should be respected by a margin in the link budget.
Please note that in CDMA-Systems the available transmit power of the ground station has to be shared between all aircraft. The calculation in the link budgets therefore assumes that at the ground station in worst-case (all aircraft are operating at the cell border with full transmit power) a total power of \( u \cdot p_u = 104 \cdot 20 \text{ Watt} = 2080 \text{ Watt} \) is available. For a cell radius of 75km 104 aircraft are found in this cell, all having simultaneous communication in uplink (from ground to aircraft). This is just a theoretical limitation. It has to be considered, that it is quite unlikely that a separate speech connection is established and active towards each aircraft at the same time because this would need 104 operators working simultaneous on ground. Typical shared channels will handle group calls where an operator is addressing several aircraft at the same time and thus reduce the maximum needed transmit power on ground. Smaller cell radius will decrease the aircraft count per cell (e.g. 47 aircraft in a cell with 50 km cell radius) and decreases transmit power requirements as well. Finally not all aircraft will operate at the cell border but closer to the base station, thus leading again to smaller transmit powers.

In downlink (aircraft to ground) each aircraft operates it’s own transmitter and therefore power sharing between different aircrafts does not occur.

**Homogenous Distribution of Aircraft**

The assumption that the aircraft are distributed homogenous in the area of the airspace sector is used, when the cells are split and the number of aircraft per cell is calculated by dividing the number of aircraft in the sector with the number of the cells per airspace sector.

During the calculation of the interference situation inside a single cell the distribution of the aircraft is not important, because power control will compensate the different path losses based on the different distances.

For adjacent cell interference the position of aircraft will become important, as aircraft close to the cell border will suffer and cause higher interference than aircraft in the middle of the cell. Depending of distribution of the aircraft different scenarios are possible. For example, in a homogenous network six other cells surround a cell. Under the assumption that each cell contains the same number of aircraft the interference coming from surrounding cells may be six times higher than interference coming from the own cell, if all aircraft are located at the cell border towards the inner cell.

A more detailed analysis under consideration of specific aircraft positions typically is done with a Monte Carlo simulation. This is outside the time frame of this study. We nevertheless assume that the consideration of adjacent cell interference with a capacity factor is sufficient regarding the overall accuracy of the applied method.

**Same Data Rate for Aircraft**

The calculations are based on the assumption that in a cell \( u \) aircraft operates a connection with the same bit rate \( r \). This bit rate \( r \) is the mean value calculated from the total throughput and the number of aircraft. In reality the throughput will consist of different data streams with different bit
rates like 20 kBit/s for speech and 384 kBit/s for video. In 3G – CDMA systems the different data rates will be transmitted with different spreading factors on the same bandwidth. For each connection the following equation has to be fulfilled[5]:

\[
\frac{E_b}{N_0_{\text{required}}} = 10 \log \frac{c/r}{n_o + i_o} \quad [\text{dBHz}]
\]  

(2-16)

If we assume that different data rates require the same Eb/No it is obvious that the received power \(c\) will become dependent from the data rate \(r\) and therefore the interference situation for each aircraft will become different. For each aircraft \(k\) in the cell the self-interference \(i_{ok}\) has to be calculated according to the following equation:

\[
i_{ok} = \sum_{j=1, j\neq k}^{n} \frac{c_j}{b} \quad (2-17)
\]

The power values \(c_j\) are dependent from each other because the power control mechanism tries to minimize the interference in the cell. Because the reception power is depending from the bit rate (see 6.2) different services will have different impact on the overall interference. Therefore for an exact modeling of the interference Equation (2-16) have to solved for each user, or at least for each service.

If the method, using averaged data rates instead of proper modeling with different data rates, will lead to valid results should be further investigated.
3. Sensitivity Analysis

The needed bandwidth for the projected communication system depends on various factors and technical parameter. At the current stage of the project not much is known about the final system and the probable range of parameter. Therefore values as defined in current 3G systems have been used for the calculations.

To ensure that the results will be as close as possible to the real system requirements, a sensitivity analysis has been performed to identify the impact of different parameters on the calculated bandwidth. Based on the results of this analysis, the parameter for the final calculations have been selected.

For the sensitivity analysis the model as developed by EUROCONTROL has been improved and used. A description of the extended model is given in Chapter 3.1, the different analyses are discussed in Chapter 3.2.

3.1. Improved Model for Bandwidth Calculation

In Chapter 2 the general feasibility of the developed EUROCONTROL model has been analyzed and the feasibility of the method for single rate systems has been acknowledged. Additionally some improvements have been implemented in an excel module that allows the analysis with a fixed RF-Bandwidth.

3.1.1. General Equation for the required Bandwidth

The base for the extended excel module is the definition of the required Eb/No [5]:

\[
e_b
\]

\[n_o \bar{\text{required}} = \frac{c/r}{n_o + i_o + i_o-\text{adj}} \]

(3-1)

With

\(c\)  Power of wanted signal

\(r\)  Data rate of the signal before spreading

\(i_o\)  Power spectral density of all interference coming from users in the cell
Equation (3-1) can be solved either for bandwidth, needed power or number of user. Equation (3-2) gives the solution for the required bandwidth that has been derived in Appendix 6.8:

\[
b = \frac{(u - 1) \cdot (1 + \alpha) \cdot r \cdot \frac{e_b}{n_o^{\text{required}}}}{1 - \frac{n_o \cdot r \cdot e_b}{c \cdot n_o^{\text{required}}}}
\]  

(3-2)

The following parameter are used in addition to equation (3-1):

- \( u \) Number of user in the cell
- \( \alpha \) Factor for adjacent cell interference

Equation (3-2) is valid under the following assumptions:

- Number of user \( u > 1 \)
- Same receive power \( c \) for all users
- Same data rate \( r \) for all users

Please note that the factor \( \alpha \) that is used to model the interference coming from adjacent cells is handled in a different way than the cell capacity factor \( \gamma \) used in the spreadsheets coming from EUROCONTROL: A value of \( \alpha = 0 \) stands for no interference from adjacent cells, whereas for example a value of \( \alpha = 0.5 \) means that the power coming from adjacent cells is 50% of the power originating from the own cell.

The cell capacity factor \( \gamma \) is defined as fraction of the capacity with adjacent cell interference to the capacity without adjacent cell interference. From equation (6-27) for the capacity of the system it can be seen that

\[
\alpha = \frac{1}{\gamma} - 1
\]  

(3-3)

\( i_{\text{adj}} \) Power spectral density of interference coming from adjacent cells

\( n_{\text{to}} \) Power spectral density of thermal noise

\( c \) Power of wanted signal
3.1.2. Impact of fixed RF-Bandwidth

In existing CDMA systems like IS-95, CDMA-2000 or UMTS the user signals will be spread to a fixed data rate the so called chip rate. To transmit this chip rate a fixed RF-bandwidth is used. The following table gives an overview on typical chip rates and RF-bandwidth:

<table>
<thead>
<tr>
<th>System</th>
<th>Chip Rate</th>
<th>Channel Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDMA-One (IS-95)</td>
<td>1,228 Mchip/s</td>
<td>1,25 MHz</td>
</tr>
<tr>
<td>UMTS</td>
<td>3,84 Mchip/s</td>
<td>5 MHz</td>
</tr>
<tr>
<td>CDMA 2000</td>
<td>3,84 Mchip/s</td>
<td>5 MHz</td>
</tr>
</tbody>
</table>

Table 1: Chip rates and channel bandwidth for commercial CDMA systems

Spreading is obtained by multiplication of the user signal with binary sequences like Walsh or OVFS-Codes. Different data rates are handled with codes of different length, only codes with a length of $2^n$ with $n$ as integer can be used. This means, that the system sometimes has to perform a rate matching before a signal can be spread. For example if a signal of 20 kBit/s shall be transmitted with a chip rate of 3,84 Mchip/s the best spreading factor to be used would be 192 ($3.84 / 0.02$). As 192 is not a power of 2 the next closest power of 2 that is smaller than 192 has to be used. This is $2^7 = 128$. Because $3.84 / 128 = 0.03$ the original signal of 20 kBit/s has to be transformed to a data rate of 30 kBit/s before spreading is applied.

The excel module has been extended to take this effect into account. In Figure 1 the results of a calculation are shown for the theoretical system and for a system using a chip rate of 3,84 Mchip/s. In both cases 38 users have been distributed in a cell with 50 km radius, for simplicity uplink and downlink are using the same technical parameter. The minimum required bandwidth according to the theoretical system is 4,22 MHz for uplink and the same for downlink. The system with the fixed chip rate needs a total bandwidth of 7,68 MHz (10 MHz when including guard bands). Since in systems with a fixed spreading rate capacity only can be increased in blocks, the resulting capacity is 46 user per cell for the second system.
Theoretical system

<table>
<thead>
<tr>
<th>UL</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.22 MHz</td>
<td>4.22 MHz</td>
</tr>
<tr>
<td>20 kBit/s</td>
<td>20 kBit/s</td>
</tr>
<tr>
<td>Spreading Factor</td>
<td>211,23</td>
</tr>
<tr>
<td>required Channels</td>
<td>1,0</td>
</tr>
</tbody>
</table>

UMTS

<table>
<thead>
<tr>
<th>UL</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MHz</td>
<td>5 MHz</td>
</tr>
<tr>
<td>3.84 MHz</td>
<td>3.84 MHz</td>
</tr>
<tr>
<td>30 kBit/s</td>
<td>30 kBit/s</td>
</tr>
<tr>
<td>Max User per Channel</td>
<td>23</td>
</tr>
<tr>
<td>req. Channels</td>
<td>2,0</td>
</tr>
<tr>
<td>required Channels</td>
<td>1,0</td>
</tr>
</tbody>
</table>

Resulting Capacity

<table>
<thead>
<tr>
<th>UL</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>38,00 User</td>
<td>38,00 User</td>
</tr>
<tr>
<td>4,22 MHz</td>
<td>4,22 MHz</td>
</tr>
<tr>
<td>Total Bandwidth</td>
<td>7,68 MHz</td>
</tr>
<tr>
<td>10 MHz</td>
<td>10 MHz</td>
</tr>
</tbody>
</table>

Total Bandwidth

<table>
<thead>
<tr>
<th>UL</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 MHz</td>
<td>10 MHz</td>
</tr>
</tbody>
</table>

Figure 1: Excel Module for theoretical System and System with fixed RF-Bandwidth

The calculation for fixed chip rate is done in the following way:

- Based on the user data rate and the chip rate, the feasible spreading factor and the channel rate are calculated.

- The following equation, as derived in Appendix 6.8, is used to calculate the maximum number of user that can be served in the bandwidth defined by the system chip rate:

\[
\frac{1 + r \cdot \left( \frac{1 + \alpha}{b} - \frac{n_o}{c} \right) \cdot \frac{e_b}{n_o^{\text{required}}}}{r \cdot (1 + \alpha) \cdot \frac{e_b}{n_o^{\text{required}}}} = u_{\text{max-per-cell}} \tag{3-4}
\]

- Finally the number of required channels is calculated by dividing the number of user in the cell by the maximum number of user per channel.

3.2. Results of Sensitivity Analysis

During the sensitivity analysis the following parameter have been varied:

- Cell radius
- Transmitter power
- Adjacent Cell Factor
- Eb/No requirement
- Transmit frequency
3.2.1. Variation of Cell Radius

In Figure 2 the required bandwidth is shown in dependency on the cell radius for three different data rates. A rate of 20 kBit/s has been selected to obtain information about the voice service. 384 kBit/s have been used to model video transmission. Additional a curve showing the sum of the bandwidth requirement for the 20kBit/s and 384 kBit/s data rates has been calculated. A data rate of 31.56 kBit/s has been used as an average of video and voice.

In Table 2 the used parameter are listed.

<table>
<thead>
<tr>
<th>Name of Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate:</td>
<td>20kBit/s, 31.56kBit/s, and 384kBit/s</td>
</tr>
<tr>
<td>Eb/N0:</td>
<td>6 dB</td>
</tr>
<tr>
<td>Adjacent cell interference factor:</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Table 2: Parameter used during Variation of Cell Radius

<table>
<thead>
<tr>
<th>Name of Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headroom for power control:</td>
<td>6 dB</td>
</tr>
<tr>
<td>Max. Transmitter power:</td>
<td>13 dBW</td>
</tr>
<tr>
<td>Number of users:</td>
<td>105 users in airspace sector for voice</td>
</tr>
<tr>
<td></td>
<td>2 users per cell for video</td>
</tr>
<tr>
<td>Cell radius:</td>
<td>variable</td>
</tr>
</tbody>
</table>

From Figure 2 it can be seen that with increasing cell radius the required bandwidth will increase as well. Two different effects can be identified as reason for this. The one can be best understood from the result for 384 kBit/s. For this data rate the number of users has been constant (2 user) during the complete calculation. The variation in bandwidth is resulting from changes in the received power at cell border. With increasing cell radius the power at cell border will get smaller and thermal noise will get more and more dominant. This can be seen direct from equation (3-2) in which the inverse of $c/n_0$ is standing in the denominator. With decreasing power the denominator will tend towards zero and therefore the required bandwidth will become infinite.

The curves for 20kBit/s and 31,56 kBit/s are showing again a rise in required bandwidth for larger cell sizes. Aside the effect that power at cell border will decrease for increasing cell radius, for this bit rates the number of users per cell has become larger with larger cell radius because a constant user density (constant number of aircraft per km$^2$) has been used. Of course this will lead to an increase in required bandwidth as well.

The sum of the results for 20 kBit/s and 384 kBit/s has been used to analyze if the calculation of the total required bandwidth based on an averaged data rate over all services is feasible or not. In Figure 2 it is shown that the summation will lead to higher bandwidth requirements than the modeling with an average data rate as the 384 kBit/s will be dominant.

### 3.2.2. Variation of Transmit Power

In Figure 3 the required bandwidth is shown for data rates of 20, 31.56 and 384 kbit/s for different transmit powers.
Parameter | Description
--- | ---
Data rate: 20kBit/s, 31,56kBit/s, 384kBit/s | 20kBit/s, 31,56kBit/s, 384kBit/s
Eb/N0: 6 dB | 6 dB
Adjacent cell interference factor: 0,4 | 0,4
Headroom for power control: 6 dB | 6 dB
Max. transmit power: Variable | Variable
Number of users: 47 user per cell for voice (equals 105 users in airspace sector), 2 user per cell for video | 47 user per cell for voice (equals 105 users in airspace sector), 2 user per cell for video
Cell radius: 35 km | 35 km
Data rate: 20kBit/s, 31,56kBit/s, 384kBit/s | 20kBit/s, 31,56kBit/s, 384kBit/s

Table 3: Parameter used during Variation of Transmit Power
From Figure 3 it can be seen, that for large values of the transmit power the required bandwidth is almost constant. When transmit power is decreased bandwidth requirement will start to increase and finally becomes infinite. This is the case when the transmit power approaches a power limit.

This effect can be understood from equation (3-2) where the term

\[
1 - \frac{n_{to} \cdot r \cdot e_b}{c \cdot n_o^{\text{required}}} \quad \text{(3-5)}
\]

is standing in the denominator. When power \( c \) is getting smaller, thermal noise power \( n_o \) will become more and more dominant. With this, the second part of the term will approach one and therefore the denominator will become zero. The power limit therefore can be expressed as

\[
c_{\text{limit}} = \frac{n_{to} \cdot r \cdot e_b}{n_o^{\text{required}}} \quad \text{(3-6)}
\]

For higher data rates this power limit is reached earlier (at higher transmit powers) than for smaller data rates.

The product of spectral power noise density and data rate \( n_{to} \cdot r \) can be understood as resulting noise power for the signal in base band. The higher the data rate, the higher the thermal noise power and therefore more reception power is needed to achieve a sufficient carrier to noise ratio.

### 3.2.3. Variation of Adjacent Cell Factor

In Figure 4 the required bandwidth is shown in dependency of the adjacent cell factor for different cell radius.
Figure 4: Required Bandwidth vs. Adjacent Cell Factor (Cell Radius as Parameter)

<table>
<thead>
<tr>
<th>Name of Parameter</th>
<th>Bit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate:</td>
<td>20kBit/s</td>
</tr>
<tr>
<td>Eb/N0:</td>
<td>6 dB</td>
</tr>
<tr>
<td>Adjacent cell interference factor:</td>
<td>Variable</td>
</tr>
<tr>
<td>Headroom for power control:</td>
<td>6 dB</td>
</tr>
<tr>
<td>Max. Transmitter power:</td>
<td>13 dBW</td>
</tr>
<tr>
<td>Number of users:</td>
<td>105 users in airspace sector</td>
</tr>
<tr>
<td>Cell radius:</td>
<td>Variable</td>
</tr>
</tbody>
</table>

Table 4: Parameter used during Variation of Adjacent Cell Factor

The diagram shows that an increase of the adjacent cell factor will lead to a rise of the required bandwidth. This can be seen immediately from (3-2), in which the resulting bandwidth is proportional to the factor \((1+\alpha)\).
3.2.4. Variation of Eb/No Requirement

In Figure 5 the required bandwidth is shown as a function of the Eb/No requirement and the cell radius:

![Figure 5: Required Bandwidth vs. Eb/No Requirement](image)

<table>
<thead>
<tr>
<th>Name of Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate:</td>
<td>20kBit/s</td>
</tr>
<tr>
<td>Eb/No:</td>
<td>Variable</td>
</tr>
<tr>
<td>Adjacent cell interference factor:</td>
<td>0,4</td>
</tr>
<tr>
<td>Headroom for power control:</td>
<td>6 dB</td>
</tr>
<tr>
<td>Max. Transmitter power:</td>
<td>13 dBW</td>
</tr>
<tr>
<td>Number of users:</td>
<td>105 users in airspace sector</td>
</tr>
<tr>
<td>Cell radius:</td>
<td>variable</td>
</tr>
</tbody>
</table>

Table 5: Parameter used during Variation of Eb/No-Requirement
From Figure 5 it can be seen, that a rise of the Eb/No requirement will lead to an increase in the bandwidth requirement. This effect can be understood from equation (3-2) that has been used in section 3.2.2 to explain the impact of transmit power. For larger cells the rise in required bandwidth is higher than for smaller ones if the Eb/No requirement is increased in the same way. This is based on the fact that larger cells are operating closer at the transmit power limit.

3.2.5. Variation of Frequency

Figure 6 shows the required bandwidth as function of the transmit frequency for different data rates. The parameters as listed in Table 6 have been used for the simulation.

![Figure 6: Required Bandwidth vs. Frequency](image-url)
Table 6: Parameter used during Variation of Frequency

<table>
<thead>
<tr>
<th>Name of Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate:</td>
<td>20 kBit/s, 384 kBit/s</td>
</tr>
<tr>
<td>Eb/N0:</td>
<td>6 dB</td>
</tr>
<tr>
<td>Adjacent cell interference factor:</td>
<td>0.4</td>
</tr>
<tr>
<td>Headroom for power control:</td>
<td>6 dB</td>
</tr>
<tr>
<td>Max. Transmitter power:</td>
<td>13 dBW</td>
</tr>
<tr>
<td>Number of users:</td>
<td>47 user per cell for voice (equals 105 users in airspace sector), 2 user per cell for video</td>
</tr>
<tr>
<td>Cell radius:</td>
<td>35 km</td>
</tr>
</tbody>
</table>

From Figure 6 it can be seen that for low data rates the required bandwidth is almost constant, whereas for higher data rates the required bandwidth will rise when the transmit frequency is increased. In fact a modification of frequency will change the reception power because the path loss depends on the frequency.

The above shown picture has been calculated over a frequency range from 150 MHz to 5 GHz. The difference in pathloss for this range equals to approx. 30 dB.
4. Calculation of required Bandwidth

The bandwidth requirements have been calculated for the following services separately:

- Voice
- Data + Security
- Commercial Data
- Video

From the individual requirements the total bandwidth has been calculated by summing up the traffic for each service.

The calculation has been done in two steps. The first step has been to determine the throughput per aircraft and service, the second step has been to calculate the bandwidth requirements with the model as described in 3.1.

4.1. Calculation of Throughput per Service and Aircraft

For the calculation of throughput the traffic figures origination from EUROCONTROL [1] have been taken and applied for year 2029. Based on this traffic estimation, two approaches have been used to determine the data rates.

The first one has been the method used by EUROCONTROL where the overall throughput (for one service) has been divided by the PIAC for year 2029 (105 aircraft for the airspace sector). The bandwidth requirement then has been calculated for a system in which 105 aircraft operated this average data rate.

For the second method a fixed channel rate has been selected for the different services. The number of channels needed to accommodate the traffic originating from the aircraft has been determined by dividing the throughput per service by the fixed channel rate. Finally the result has been rounded up to the next integer. For this calculation the PIAC for 2029 has been used, no modeling with Erlang B or Erlang C has been applied. This is justified because the safety-of-life applications in aviation do not allow blocking. Based on these results again the required bandwidth has been determined. The calculation has been performed without fixed RF-bandwidth, for a chip rate of 3,84 Mchip/s, and a chip rate of 1,2288 Mchip/s.

For current 3G systems like UMTS coding rates of 1/2 and 1/3 are specified [14]. A code rate of 1/3 will lead on the one hand to a better protection of the signal; on the other hand this will in-

---

1 In this group ATC data, flight recorder data and additional monitoring data has been considered together
crease the bandwidth requirement. Typically with higher coding rates the Eb/No requirements can be less stringent which will lead to lower bandwidth requirements. Since at the current state of the project not enough is known to get an exact modeling, a coding rate of 1/2 has been selected and at the same time a medium Eb/No requirement has been used. This is in accordance with the values applied by the UMTS forum for spectrum calculations [11].

The coding rate has been applied before the required number of channels has been calculated.

The calculated throughput for the services, the used channel rates and the required number of channels is given in Table 7, the detailed parameter used for throughput calculations are found in Appendix 6.2.

<table>
<thead>
<tr>
<th></th>
<th>Throughput all a/c in kBit/s</th>
<th>Fixed channel rate in kBit/s</th>
<th>Required number of channels²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>870,41</td>
<td>20</td>
<td>44 (43,52)</td>
</tr>
<tr>
<td>UL</td>
<td>870,41</td>
<td>20</td>
<td>44 (43,52)</td>
</tr>
<tr>
<td>Data+Security</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>809,17</td>
<td>64</td>
<td>13 (12,64)</td>
</tr>
<tr>
<td>UL</td>
<td>3,14</td>
<td>64</td>
<td>1 (0,05)</td>
</tr>
<tr>
<td>Commercial Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>197,60</td>
<td>64</td>
<td>4 (3,09)</td>
</tr>
<tr>
<td>UL</td>
<td>197,60</td>
<td>64</td>
<td>4 (3,09)</td>
</tr>
<tr>
<td>Video</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>768,00</td>
<td>384</td>
<td>2</td>
</tr>
<tr>
<td>UL</td>
<td>0</td>
<td>384</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7: Calculation of required Channels

Additional to the calculation per service, in section 4.7 an average data rate for all services (including coding) has been determined and the bandwidth requirement has been calculated. This corresponds to the method used by EUROCONTROL in [1].

² Figures in brackets are calculated channel requirements before rounding
4.2. System Parameter used for Calculation

In Table 8 the general and electrical parameter that have been used for the calculation are shown. The parameters have been selected based on results of the sensitivity analysis and figures found in literature. For selected parameter a short discussion is given in the following sections.

<table>
<thead>
<tr>
<th>Power Settings</th>
<th>General Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uplink (to a/c)</td>
</tr>
<tr>
<td>Transmitter Power</td>
<td>13.0</td>
</tr>
<tr>
<td>Transmit Antenna Gain</td>
<td>6.0</td>
</tr>
<tr>
<td>Receive Antenna Gain</td>
<td>0.0</td>
</tr>
<tr>
<td>LNA noise factor</td>
<td>1.0</td>
</tr>
<tr>
<td>cable/guide and diplexer insertion losses</td>
<td>3.0</td>
</tr>
<tr>
<td>Polarisation loss</td>
<td>0.5</td>
</tr>
<tr>
<td>Headroom for power control</td>
<td>6.0</td>
</tr>
<tr>
<td>Eb/No</td>
<td>6.0</td>
</tr>
<tr>
<td>Cell radius</td>
<td>50.0</td>
</tr>
<tr>
<td>Adjacent cell factor</td>
<td>0.6</td>
</tr>
<tr>
<td>Soft Handover Factor</td>
<td>0.25</td>
</tr>
<tr>
<td>LFPTMA Area</td>
<td>18385</td>
</tr>
<tr>
<td>Number aircrafts</td>
<td>104.9</td>
</tr>
<tr>
<td>System Temperature</td>
<td>290</td>
</tr>
<tr>
<td>Transmit frequency</td>
<td>5120</td>
</tr>
<tr>
<td>Boltzman const.</td>
<td>1.38E-23</td>
</tr>
</tbody>
</table>

Table 8: Power and General Calculation Parameters

From the analysis in 3.2.2 it can be seen that the bandwidth requirement is almost independent of the available transmit power (and therefore as well of additional parameter like cable losses and antenna gains), if the system is not operating close to the power limit. This power limit either is reached when the path loss is too high (cell radius is too large) or the transmit power is too low. Transmit power and cell radius therefore cannot be discussed separately.

From Figure 2 in Chapter 3.2.1 it can be seen that the maximum cell range that may be used for video is around 50 km. This corresponds to an available transmit power of 10 dBW per video connection for downlink. For larger cell radius the bandwidth requirement for video will rise over all bounds.

On the other hand, a cell radius of 50 km and a transmit power of 10 dBW in downlink offers enough power to the system to maintain several connections for voice (20 kBit/s) and data (64 kBit/s) in parallel. This is not the case when additional video transmission has to be used. In this case additional 10 dBW are required. This implies that an aircraft that has to operate video will need an extra power amplifier for video on board.

Because on the one hand larger cell radius will increase the bandwidth requirements, but on the other hand smaller cell radius will decrease the economical feasibility of the system, the 50 km cell range has been selected as compromise for the simulations. The determination of final cell
sizes is typically subject of radio network planning, where cell radius will be adjusted according to cell traffic.

An Eb/No requirement of 6 dB has been used for all services. In literature Eb/No requirements vary from 2 to 10 dB (e.g. [8],[13],[15],[16]) depending on propagation environment, data rate, modulation scheme and other factors. For example in UMTS Eb/No requirements are different for uplink and downlink because different modulation schemes are applied. Additional Eb/No figures are not fixed but will be adjusted by means of power control to obtain a specific bit error rate defined by QoS criteria. Eb/No requirements in literature therefore are typically related to a specific BER and have been obtained from simulations. The selected figure of 6 dB corresponds to a BER of 10-3 for voice transmission. For data transmission figures in a range of 3 to 4 dB are given for a BER of 10-6. Smaller values for higher data rates are found because in UMTS power control will work more accurate when higher data rates are transmitted. As it is not known if for the future system similar effects will occur the same Eb/No requirement has been used for voice and data services. This is conservative regarding the bandwidth requirement for data transmission.

For the adjacent cell factor, different figures are found in literature, a typical value is around 0.6 [8],[16]. Therefore this value has been used for the calculations. In fact much higher values may be possible as well. For example, in a homogenous network six other cells surround a cell. Under the assumption that each cell contains the same number of aircraft the largest value for the adjacent cell factor is six, if all aircraft are located at the cell border towards the inner cell and interference is only respected from this first tier. This would be a violation of the assumption of homogenous spatial distribution that has been used throughout the study and should be the topic of further investigations.

The soft handover factor models the higher interference and load in a cell originating from handover is considered. A value of 0.25 has been used.[8]

The transmit frequency has been set to 5,12 GHz. This corresponds to the worst case inside the possible frequency range.

4.3. **Required Bandwidth for Voice**

<table>
<thead>
<tr>
<th>Voice EUROCONTROL</th>
<th>Voice with Channels</th>
<th>Voice 3,84 Mchips</th>
<th>Voice 1,2288 MChips</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL</td>
<td>DL</td>
<td>UL</td>
<td>DL</td>
</tr>
<tr>
<td>Required Bandwidth</td>
<td>2.45</td>
<td>2.46</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Table 9: Required Bandwidth for Voice in MHz
For voice a channel bit rate of 20 kBit/s (including coding) has been used. The average data rate for EUROCONTROL method has been 8,29 kBit/s.

4.4. Required Bandwidth for Data and Security

For the modeling with channels the data throughput for one aircraft originating from the different sources (ATC Data, Monitoring Data, Flight Recorder Data) has been summed up and mapped on 64 kBit/s channels (after coding). For the EUROCONTROL method 20,4 kBit/s in DL and 12,8 kBit/s in uplink has been used.

<table>
<thead>
<tr>
<th>Required Bandwidth</th>
<th>Data &amp; Security EUROCONTROL</th>
<th>Data &amp; Security Channels 3,84 Mchips</th>
<th>Data &amp; Security 1,2288 MChips</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL</td>
<td>3,81</td>
<td>0,44</td>
<td>1,25</td>
</tr>
<tr>
<td>DL</td>
<td>6,15</td>
<td>2,23</td>
<td>2,5</td>
</tr>
<tr>
<td>UL</td>
<td>0,44</td>
<td>5</td>
<td>1,25</td>
</tr>
<tr>
<td>DL</td>
<td>2,23</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Required Bandwidth for Data and Security in MHz

4.5. Required Bandwidth for Commercial Data

Commercial data has been mapped on 64 kBit/s channels (after coding), an average data rate of 1,88 kBit/s for uplink and downlink has been used for EUROCONTROL approach.

<table>
<thead>
<tr>
<th>Required Bandwidth</th>
<th>Commercial EUROCONTROL</th>
<th>Commercial Channels 3,84 Mchip/s</th>
<th>Commercial 1,2288 Mchip/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL</td>
<td>0,55</td>
<td>0,44</td>
<td>1,25</td>
</tr>
<tr>
<td>DL</td>
<td>0,55</td>
<td>0,45</td>
<td>1,25</td>
</tr>
<tr>
<td>UL</td>
<td>0,44</td>
<td>5</td>
<td>1,25</td>
</tr>
<tr>
<td>DL</td>
<td>0,45</td>
<td>5</td>
<td>1,25</td>
</tr>
</tbody>
</table>

Table 11: Required Bandwidth for Commercial Data in MHz

3 During calculations done in [1] a channel mapping for data services has been done. This method has been applied in the same way for this calculation. See Appendix 6.3 for more details.
4.6. Required Bandwidth for Video

For video it has been assumed that two channels with 384 kBit/s (after coding) will be needed, for EUROCONTROL approach 7.32 kBit/s have been used.

<table>
<thead>
<tr>
<th>Required Bandwidth</th>
<th>Video EUROCONTROL</th>
<th>Video Channels</th>
<th>Video 3,84 Mchips</th>
<th>Video 1,2288 Mchips</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL</td>
<td>DL</td>
<td>UL</td>
<td>DL</td>
<td>UL</td>
</tr>
<tr>
<td>0</td>
<td>2.17</td>
<td>0</td>
<td>5.12</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 12: Required Bandwidth for Video in MHz

4.7. Required Bandwidth for averaged Data Rate

In this calculation the average data rate has been determined to 22.97 kBit/s for uplink and 37.89 kBit/s for downlink (including video). Simulation has been performed for 105 users in the airspace sector.

<table>
<thead>
<tr>
<th>Required Bandwidth</th>
<th>Averaged data rate EUROCONTROL</th>
<th>Averaged data rate Channels</th>
<th>Averaged data rate 3,84 Mchips</th>
<th>Averaged data rate 1,2288 MChips</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL</td>
<td>DL</td>
<td>UL</td>
<td>DL</td>
<td>UL</td>
</tr>
<tr>
<td>6.92</td>
<td>11.71</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A</td>
</tr>
</tbody>
</table>

Table 13: Required Bandwidth for averaged Data Rate in MHz
4.8. Total Bandwidth Requirement

The total bandwidth requirement for the system has been calculated by summing up the results obtained for each service in the sections 4.3 to 4.6. For the method based on the theoretical model additional bandwidth for guard bands (5%) and for protocol overhead (20%) have been added. These values have been taken from [11].

As the systems with a fixed RF-Bandwidth (Chip rate of 3,84 Mchip/s and 1,2288 Mchip/s) already comprises additional spectrum for guard bands and spare capacity for system management is available, no corrections have been applied to these results.

<table>
<thead>
<tr>
<th></th>
<th>Total Sum EUROCONTROL</th>
<th>Total Sum Channel Modeling</th>
<th>Total Sum 3,84 Mchip/s</th>
<th>Total Sum 1,2288 Mchip/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL</td>
<td>DL</td>
<td>UL</td>
<td>DL</td>
<td>UL</td>
</tr>
<tr>
<td>Required Bandwidth</td>
<td>6,81</td>
<td>11,33</td>
<td>3,36</td>
<td>10,29</td>
</tr>
<tr>
<td>Protocol Overhead 20%</td>
<td>1,36</td>
<td>2,27</td>
<td>0,67</td>
<td>2,06</td>
</tr>
<tr>
<td>Guard Band 5%</td>
<td>0,34</td>
<td>0,57</td>
<td>0,17</td>
<td>0,51</td>
</tr>
<tr>
<td>Total required Bandwidth</td>
<td>8,51</td>
<td>14,17</td>
<td>4,2</td>
<td>12,86</td>
</tr>
<tr>
<td>Total required Bandwidth (UL + DL)</td>
<td>22,68</td>
<td>17,06</td>
<td>45</td>
<td>18,75</td>
</tr>
</tbody>
</table>

Table 14: Total Bandwidth Requirements in MHz including Video

Refraining from the case with a chip rate of 3,84 Mchip/s the total bandwidth requirements found in Table 14 are in the same range for downlink of around 12 to 14 MHz, the calculation with channels (but without fixed chip rate) needs with approx. 4 MHz less bandwidth than the two other methods that needs around 8 MHz. The calculation with a chip rate of 1,2288 Mchip/s leads to smaller values because in this model only approx. 2 % are reserved for guard bands and protocol overhead.
The calculation based on a fixed chip rate of 3,84 Mchip/s leads to higher bandwidth requirements that the other methods. This can be understood from the low granularity of the system in which bandwidth only can be allocated in 5 MHz blocks. Since for each service at least 5 MHz have to be allocated for a system that operates 3 services the minimum required bandwidth result to 3x5 MHz. A use of free capacity in a frequency block by another service (e.g. usage of free capacity for data services inside the spectrum allocated for voice) is not modeled with this approach, the achieved total bandwidth requirements for the 3,84 Mchip/s system therefore have to be handled with care.

In Table 15 the total bandwidth requirement is given without the video service:

<table>
<thead>
<tr>
<th></th>
<th>Total Sum EUROCONTROL</th>
<th>Total Sum Channel Modeling</th>
<th>Total Sum 3,84 Mchip/s</th>
<th>Total Sum 1,2288 Mchip/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UL</td>
<td>DL</td>
<td>UL</td>
<td>DL</td>
</tr>
<tr>
<td>Required Bandwidth</td>
<td>6,81</td>
<td>9,16</td>
<td>3,36</td>
<td>5,17</td>
</tr>
<tr>
<td>Protocol Overhead 20%</td>
<td>1,36</td>
<td>1,83</td>
<td>0,67</td>
<td>1,03</td>
</tr>
<tr>
<td>Guard Band 5%</td>
<td>0,34</td>
<td>0,46</td>
<td>0,17</td>
<td>0,26</td>
</tr>
<tr>
<td>Total required Bandwidth</td>
<td>8,51</td>
<td>11,45</td>
<td>4,2</td>
<td>6,46</td>
</tr>
<tr>
<td>Total required Bandwidth (UL + DL)</td>
<td>19,96</td>
<td>10,66</td>
<td>35</td>
<td>16,25</td>
</tr>
</tbody>
</table>

Table 15: Total Bandwidth Requirements in MHz without Video

As video is only used in downlink, downlink values in Table 15 are smaller than the results obtained in Table 14, whereas the other values remain the same.
4.9. **Comparison of used Methodology with Methodology defined by ITU**

The used methodology in Section 4 of this document is very close to the method defined by the ITU for terrestrial cellular networks like UMTS or IMT-2000 in [12] and applied by the ITU in [10] and the UMTS Forum in [11]. The structure of the two methods is shown in Figure 7:

![Figure 7: Comparison of Methodology used to calculate the Bandwidth Requirements](image)

The major difference between the methods is the way in which bandwidth requirements are obtained from the offered traffic. ITU methodology uses the net system capability that is a measure of the system capacity of a specific technology. It is related to the spectral efficiency of mobile communication systems but contains many other factors. The net system capability has the unit dimension of kBit/s/MHz/cell. It is comprised of a number of effects that are combined in a complex manner appropriate to the radio transmission technology, the service type and the
environment. For existing systems it is typically obtained from the results of system simulations [12]. However the method to obtain this value is not defined in [10] or [12].

The approach in this document uses the estimated throughput per service as input for the model that calculates the required bandwidth needed to carry the traffic without determining the net system capability.

For traffic modeling the ITU methodology uses blocking probabilities for calculation of the needed network resources on the air interface, traffic calculations are first done on cell level for different service environments and than are generalized for the complete system.

During the traffic calculations done in this paper no blocking modeling has been applied, due to the safety-of-life applications in aviation. Throughput values have fist been calculated for the complete network and allocated to cells during bandwidth determination because the cell radius is a parameter of the applied model for the bandwidth calculation.

In the ITU methodology, the results for the different services are multiplied with the weighting factor $\alpha$, the total bandwidth requirement is multiplied with the adjustment factor $\beta$ to achieve the final bandwidth.

Weighting factor $\alpha$ is used to adjust for geographical offsets in overlapping environments and to correct effects for non-simultaneous busy hour traffic requirements. Because nothing else is known at the current stage of the project all services are assumed to have coincident busy hours and are collocated in the same geographical area. The weighting factors therefore have been set to one during the calculations.

The adjustment factor $\beta$ is used to model the impact of effects like trunking inefficiency, spectrum sharing with other communication systems in the same band, guard bands etc.

Factor $\beta$ has been set to 1,05 and applied to the bandwidth requirement of each service. This allows to judge each service separately and leads to the same result as the method defined by ITU where $\beta$ is applied to the final bandwidth.
4.9.1. Comparison of Net System Capabilities

In Table 16 different figures of the net system capabilities for GSM and IMT 2000 are given. The values have been taken from publications of the ITU [10] and [12] and the UMTS Forum [11].

Additional an estimation of the net system capability for the projected aviation system has been obtained from the bandwidth calculations performed in the sections above. For this the calculated throughput in Table 7 has been summed up for uplink and downlink. Voice and data services have been considered separately, for data the sum for security, commercial data and video transmission has been taken. Overall throughput has been divided by the bandwidth requirements and the number of cells for the Paris air space sector. A cell radius of 50 km results in a number of 2,3 cells for the whole area. Bandwidth requirements for voice have been taken from Table 9, for data the figures from Table 10 to Table 12 have been summed up. The calculation has been performed for the approach with channel mapping.

<table>
<thead>
<tr>
<th>Service</th>
<th>GSM</th>
<th>IMT 2000</th>
<th>Aviation System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UMTS Forum Report No. 6</td>
<td>ITU-R M.1390</td>
<td>ITU-R M.2023</td>
</tr>
<tr>
<td>Voice Service</td>
<td>54</td>
<td>67</td>
<td>40 - 100</td>
</tr>
<tr>
<td>Data Service</td>
<td>-</td>
<td>73</td>
<td>50 - 200</td>
</tr>
</tbody>
</table>

Table 16: Net System Capabilities in kBit/s/cell/MHz

A comparison of the net system capabilities shows, that the value of 153 kBit/s/cell/MHz achieved for the aviation system is considerable higher than the values given for IMT 2000 and GSM. The value of 99 kBit/s/cell/MHz for data services is in the range given by ITU but smaller than the one for voice service. This is not in accordance with the values given by ITU, where the net system capability for data services tends to be higher than the one for speech services. A reason for this may be that the bandwidth requirements for voice and data services have been calculated with the same Eb/No requirement. Therefore the net system capability for data has been recalculated with an Eb/No requirement of 2 dB for video has been set to 2dB. In this case a net system capability of 180 kBit/s/cell/MHz for data services is obtained.

^4 The net system capability of 180 kBit/s/cell/MHz is obtained when an Eb/No requirement of 2dB is used for the video service.
5. Conclusion

In Chapter 4 the required bandwidth for a future aeronautic system has been calculated. Since
the final system technology is not yet known, calculations have been performed for an exam-
ple system using CDMA technology. Technical parameters for the calculation have been se-
lected in accordance with typical existing cellular CDMA-Systems and aeronautical require-
ments.

The bandwidth calculations have been done separately for different services with a single rate
model that has been developed by EUROCONTROL and validated and extended in this study
by DFS / LS telcom. The overall bandwidth requirement has been obtained by summing up the
requirements for each service.

The obtained result can be understood as a provisional value for the required bandwidth, be-
because the used approach does not model the impact of interference originating from simultane-
ous transmission of different services (with different data rates) in one cell. The consideration of
the inter service interference may lead to higher bandwidth requirements than those calculated
in this study.

To consolidate the calculations further studies therefore should examine the impact of multi rate
transmission in more detail (A motivation for this is given in Appendix 6.2). At the same time
more accurate models could replace some approximations that have been used during band-
dwidth calculation. This comprises the used homogenous spatial distribution of the aircraft and
the modeling of the interference coming from adjacent cells.

The overall structure of the calculations are based on recommendations issued by the ITU in
[12] and [10]. Nevertheless some differences are found in the way, how the number of required
channels is calculated that are necessary to serve the offered voice and data traffic. An imple-
mentation of the Erlang B calculation for circuit switched and Erlang C calculation for packet
switched traffic would correspond better to the method as used by ITU and for traffic dimen-
sioning of communication networks in general. Nevertheless, because safety-of-life applications
in aviation do not allow blocking, the used approach is justified.
6. Appendix

6.1. References

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6.2. Motivation for Multi Rate Model

The main limitation of the used single rate model is, that the model has been derived under the assumption that all links in a cell are using the same data rate (we therefore refer this model as single-rate model in the following) and that power control will obtain the same receive power \( c \) for all connections. This does not correspond to the requirements of a system in which different services like voice and data will be operated simultaneous and multiple access will be obtained by code division technology.

Two main issues can be pointed out that will have an impact on the required bandwidth:

- Impact of spreading factor
- Impact of inter service interference

Impact of Spreading Factor

A fundamental concept of spread spectrum CDMA systems is, that a signal with the bandwidth \( r \) is transmitted by using a bandwidth \( b \) with typically \( b > r \). The ratio \( b/r \) is called the spreading factor \( s \). The impact of the spreading factor can be understood by analyzing the basic equation for the required \( E_b/N_0 \) that has to be fulfilled for each connection:

\[
\frac{e_b}{n_{0 \text{ required}}} = \frac{c/r}{n_{so} + i_o + i_{o-adj}} \quad (6-1)
\]

With
- \( i_o \) : Power spectral density of all interference coming from users in the cell
- \( i_{o-adj} \) : Power spectral density of interference coming from adjacent cells
- \( n_{so} \) : Power spectral density of thermal noise
- \( c \) : Power of wanted signal

Equation (6-1) can be transformed to equation (6-2) that allows discussing the impact of the spreading factor (see Appendix 6.9):
\[
\frac{e_b}{n_{o\text{ required}}} = \frac{c}{n_i + \frac{i}{s}} \quad (6-2)
\]

With

\[ s = \frac{b}{r} \quad \text{Spreading factor} \]

\[ i \quad \text{Total interfering power in the cell without thermal noise} \]

\[ n_i \quad \text{Thermal noise power in the cell} \]

For further discussion it is assumed that the impact of thermal noise can be neglected and logarithmic values are used:

\[
\frac{E_b}{N_o\text{ required}} = 10\log \frac{e_b}{n_o\text{ required}} \approx 10\log \frac{c}{i/s} = 10\log c + 10\log s - 10\log i \quad (6-3)
\]

From equation (6-2) and (6-3) it can be seen that the power coming from self-interference of the system will be reduced, if the spreading factor \( s \) is larger than one. The term \( 10\log s \) is called the spreading gain.

In existing systems all services will be spread to the same RF-bandwidth \( b \) and therefore services with high data rates will have smaller spreading factors than services with low data rates. As a consequence the spreading gain will be smaller for services with high data rates and more power \( c \) is needed to achieve the same Eb/No requirement. This can be seen from equation (6-3) under the assumption that the interfering power \( i \) is the same for all users. (In Appendix 6.10 it is shown that this assumption is valid for a large number of users)

Even if smaller Eb/No requirements are assumed for higher data rates, \( c \) has to be larger compared to services with low data rates because the difference in the spreading gain \( 10\log(s) \) is larger than the difference in the Eb/N0 requirements (see Table 17).
From the above said it can be concluded that for a multi rate system, different receive powers will be adjusted by power control for the various services.

### Interference between Different Services

As in a multi rate system different services will be operated at the same time in the same bandwidth, the services will interfere with each other.

If for example a cell is loaded with \( u \) voice users and \( v \) data users, the interference for a specific voice user will come from \( u-1 \) voice users and \( v \) data users. The interference for a specific data user will come from \( u \) voice users and \( v-1 \) data users.

When the single rate model is used separately for voice and data and afterwards the bandwidth requirements will be summed up over all services, the final result will underestimate the requirements for the future system. The reason for this is, that the single rate calculation for voice will neglect the interference caused by data users and the single rate calculation for data will neglect the interference caused by voice users. As interference is dependant on the one hand from the used power level for the transmission and on the other hand the used power is dependant of the interference level in the cell, the calculation cannot be done separately for voice and data.

---

Please note that the values are dependant of various factors like channel mapping, propagation environment, speed of users etc.

---

**Table 17: Sample values for Spreading Gain and Eb/No\(^5\) for UMTS services [13]**

<table>
<thead>
<tr>
<th>Service</th>
<th>Spreading Gain ( 10 \log_{10} s )</th>
<th>( \frac{E_b}{N_0} ) required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>( 10 \log (128) \approx 21 \text{ dB} )</td>
<td>6.5 dB</td>
</tr>
<tr>
<td>384 kBit/s</td>
<td>( 10 \log (8) \approx 9 \text{ dB} )</td>
<td>4 dB</td>
</tr>
</tbody>
</table>

\(^5\) Please note that the values are dependant of various factors like channel mapping, propagation environment, speed of users etc.
### 6.3. Used Parameter for Throughput Calculation

<table>
<thead>
<tr>
<th>Voice</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>data rate per voice channel</td>
<td>20 kBit/s</td>
<td></td>
</tr>
<tr>
<td>no of flights</td>
<td>98%</td>
<td></td>
</tr>
<tr>
<td>no of calls</td>
<td>6 calls</td>
<td></td>
</tr>
<tr>
<td>no of flights</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>no of calls</td>
<td>3 calls</td>
<td></td>
</tr>
<tr>
<td>average call duration</td>
<td>11 s</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>DL</th>
<th>UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW (netto) / ac</td>
<td>1.88 kBit/s</td>
<td></td>
</tr>
<tr>
<td>BW (netto) / all ac</td>
<td>197.60 kBit/s</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>DL</th>
<th>UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. operator tolerable loading</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>additional channels</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>protocol overhead</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>code rate</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>BW (brutto)</td>
<td>870.41 kBit/s</td>
<td></td>
</tr>
<tr>
<td>BW (brutto) per a/c</td>
<td>8.29 kBit/s</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8: Voice Traffic Calculation
The original calculation coming from EUROCONTROL [1] uses for data services a channel mapping to channels with a rate of 64 kBit/s. The achieved throughput that has been achieved from this method is given in Line 2) of Figure 9. This value has been used for the bandwidth calculation using an average data rate. For the bandwidth calculation using channel mapping the value coming from Line 1) of Figure 9 has been used (after applying of a code rate of $\frac{1}{2}$).
Figure 10: Commercial Data Traffic Calculation

Figure 11: Security Data Traffic Calculation
### Figure 12: Video Traffic Calculation

<table>
<thead>
<tr>
<th></th>
<th>DL</th>
<th>UL</th>
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</thead>
<tbody>
<tr>
<td>no. of monitored ac</td>
<td>192</td>
<td>0</td>
</tr>
<tr>
<td>BW (netto) / cell</td>
<td>384</td>
<td>0 kBit/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>handover factor</td>
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</tbody>
</table>

<table>
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<tr>
<th></th>
<th>0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>protocol overhead</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>0,50</th>
</tr>
</thead>
<tbody>
<tr>
<td>code rate</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>768,00</th>
<th>0,00 kBit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW (brutto)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>7.32</th>
<th>0 kBit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW (brutto) per a/c</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.4. Mathematical Conventions

To distinguish between logarithmic values in dB and linear values, uppercase letters for logarithmic and lowercase letters for linear values will be used. Fractions of uppercase letters means the logarithmic value of the fraction of the related linear values:

\[
\frac{C}{I} = 10 \log \left( \frac{C}{I} \right) = 10 \log C - 10 \log I = C - I \quad [\text{dB}]
\]

The function “log” stands for the logarithm to the base 10.

The suffix o will be used to mark power spectral density e.g.:

\[
n = n_o \cdot b \Rightarrow \text{noise power} = \text{noise spectral density} \cdot \text{receiving bandwidth}
\]

The following letters will be used:

c: carrier power [W]
u: Number of users [dimensionless]
i_o: interference power spectral density [W/Hz]
n_o: noise power spectral density [W/Hz]
n_t: thermal noise power spectral density [W/Hz]
e_b: energy per information bit [J]
r: data rate
b: bandwidth
6.5. Calculation of C/No from C/lo and C/Nto:

\[
\frac{C}{N_o} = -10 \log (10^{\frac{C}{10 N_o}} + 10^{\frac{C}{10 N_o}})
\]

\[
= -10 \log (10^{-10 \log 10^{\frac{n_o}{10}} + 10^{-10 \log 10^{\frac{n_o}{10}}}})
\]

\[
= -10 \log (10^{\frac{n_o}{c}} + 10^{\frac{i_o}{c}})
\]

\[
= -10 \log \frac{n_o + i_o}{c}
\]

\[
= 10 \log \frac{c}{n_o + i_o}
\]
6.6. Calculation of B based on C/lo required and u

From
\[
\frac{C}{I_{\text{available}}} = 10 \log \frac{C}{i_o} \cdot b = 10 \log \frac{C}{i_o} - 10 \log b = \frac{C}{I_{\text{o available}}} - 10 \log b
\]  \tag{6-5}

and Equation (2-3):
\[
\frac{C}{I_{\text{available}}} = -10 \log u
\]  \tag{6-6}

follows
\[
B = 10 \log b = \frac{C}{I_{\text{o available}}} + 10 \log u
\]  \tag{6-7}

For a proper working system the following requirement has to be fulfilled:
\[
\frac{C}{I_{\text{o available}}} \geq \frac{C}{I_{\text{o required}}} \quad \text{or at least} \quad \frac{C}{I_{\text{o available}}} = \frac{C}{I_{\text{o required}}}
\]  \tag{6-8}

with this finally we get
\[
B = 10 \log b = \frac{C}{I_{\text{o required}}} + 10 \log u
\]  \tag{6-9}
6.7. Modeling of Factor for Adjacent Cell Interference:

Starting point is equation (6-9)

\[ B = 10 \log \frac{C}{I_b} \]  
\[ + 10 \log u \]  
(6-10)

as derived in Appendix 6.6.

Under the assumption that \( N_o >> N_t \) or \( u \cdot c >> n_1 \) follows

\[ B = \frac{C}{I_b} \]  
\[ + 10 \log u = \frac{C}{N_o} \]  
\[ + 10 \log u = \frac{E_b}{N_o} \]  
\[ + 10 \log r + 10 \log u \]  
(6-11)

B equals the needed bandwidth without adjacent cell interference. If \( r' \) comprises the effects of adjacent channel interference we get

\[ B' = \frac{E_b}{N_o} \]  
\[ + 10 \log r' + 10 \log u \]  
(6-12)

for the needed bandwidth \( B' \) with adjacent cell interference. With

\[ r' = \frac{r}{\gamma} \]  
(6-13)

we get

\[ B' = \frac{E_b}{N_o} \]  
\[ + 10 \log \frac{r}{\gamma} + 10 \log u = \frac{E_b}{N_o} \]  
\[ + 10 \log r + 10 \log \frac{u}{\gamma} \]  
(6-14)

From (2-3)
\[ \frac{C}{I_{\text{available}}} = -10 \log u = 10 \log \frac{c}{i} \]  

(6-15)

follows

\[ \frac{C}{I_{\text{available}}} = -10 \log u = 10 \log \frac{c}{i} \]  

(6-16)

and therefore

\[ 10 \log \frac{u}{\gamma} = -10 \log \frac{c}{i} - 10 \log \gamma = 10 \log \frac{i}{\gamma} \]  

(6-17)

With

\[ i' = \frac{i}{\gamma} \]  

(6-18)

we see that values of \( \gamma < 1 \) in fact will increase the interference in the cell.
6.8. General Equation for the Calculation of the required Bandwidth $b$

$$\left. e_b \right|_{n_o \text{ required}} = \frac{c}{r \cdot n_o + i_o + i_{o-adj}} = \frac{c}{r \cdot (n_o + (u - 1) \cdot \frac{c}{b} + i_{o-adj})} \quad (6-19)$$

$$i_{o-adj} = i_o \cdot \alpha = (u - 1) \cdot \frac{c}{b} \cdot \alpha \quad (6-20)$$

with (6-20) in (2-1):

$$\left. e_b \right|_{n_o \text{ required}} = \frac{c}{r \cdot (n_o + (u - 1) \cdot \frac{c}{b} \cdot (1 + \alpha))} = \frac{1}{r \cdot c \cdot n_o + (u - 1) \cdot \frac{r}{b} \cdot (1 + \alpha)} \quad (6-21)$$

$$\frac{r}{c} \cdot n_o \cdot \frac{e_b}{n_o \text{ required}} + (u - 1) \cdot \frac{r}{b} \cdot (1 + \alpha) \cdot \frac{e_b}{n_o \text{ required}} = 1 \quad (6-22)$$

with

$$\varepsilon = \left. e_b \right|_{n_o \text{ required}} \quad (6-23)$$

$$\frac{r}{c} \cdot n_o \cdot \varepsilon + (u - 1) \cdot \frac{r}{b} \cdot (1 + \alpha) \cdot \varepsilon = 1 \quad (6-24)$$
Solving (6-24) for Bandwidth $b$

$$b = \frac{r \cdot (u - 1) \cdot (1 + \alpha) \cdot \epsilon}{1 - \frac{n_{to}}{c} \cdot r \cdot \epsilon}$$ (6-25)

Solving (6-24) for power $c$

$$c = \frac{r \cdot n_{to} \cdot \epsilon}{1 - (u - 1) \cdot (1 + \alpha) \frac{r}{b} \cdot \epsilon}$$ (6-26)

Solving (6-24) for number of user $u$ (Capacity of cell)

$$u = \frac{1 + r \cdot \epsilon \cdot \left(\frac{1 + \alpha}{b} - \frac{n_{to}}{c}\right)}{\frac{r}{b} \cdot \epsilon \cdot (1 + \alpha)}$$ (6-27)
6.9. Impact of Spreading Factor

\[ \frac{e_b}{n_{\text{required}}} = \frac{c/r}{n_{to} + i_o + i_{o-adj}} \]  \hspace{1cm} (6-28)

With

- \( i_o \) : Power spectral density of all interference coming from users in the cell
- \( i_{o-adj} \) : Power spectral density of interference coming from adjacent cells
- \( n_{to} \) : Power spectral density of thermal noise
- \( c \) : Power of wanted signal

When we define that the interference coming from adjacent cells is a fraction of the interference coming from the own cell we can write

\[ i_{\text{total}} = n_{to} + i_o + i_{o-adj} = n_{to} + i_o + \alpha \cdot i_o = n_{to} + (\alpha + 1) \cdot i_o \]  \hspace{1cm} (6-29)

and therefore

\[ \frac{e_b}{n_{\text{required}}} = \frac{c}{r} \cdot \frac{1}{n_{to} + (\alpha + 1) \cdot i_o} = \frac{c}{r \cdot n_{to} + (\alpha + 1) \cdot (u - 1) \cdot c \cdot \frac{r}{b}} \]  \hspace{1cm} (6-30)

With this, the interference coming from the system itself can be written as

\[ i = (\alpha + 1) \cdot (u - 1) \cdot c \]  \hspace{1cm} (6-31)

and the power of the thermal noise before decoding will become

\[ n_t = r \cdot n_{to} \]  \hspace{1cm} (6-32)
Finally we find

\[ \frac{e_b}{n_{0\text{ required}}} = \frac{c}{n_i + i \cdot \frac{r}{b}} = \frac{c}{n_i + \frac{i}{s}} \]  

(6-33)

with

\[ s = \frac{b}{r} \]

Spreading factor
6.10. Sample Calculation of Interference Situation for Cell with two Services

Under the assumption that in a cell two services are operating with

\[ c_1, c_2 \quad \text{Receive power for service 1 and service 2} \]

\[ u_1, u_2 \quad \text{Number of users for service 1 and service 2} \]

the interference for a user operating service 1 can be written as

\[ i_1 = (u_1 - 1) \cdot c_1 + u_2 \cdot c_2 + i_{\text{adjacent-cell}} \] (6-34)

and the interference for a user operating service 2 can be written as

\[ i_2 = u_1 c_1 + (u_2 - 1) \cdot c_2 + i_{\text{adjacent-cell}} \] (6-35)

Under the assumptions \( u_1 >> 1 \) and \( u_2 >> 1 \) it is obvious that

\[ i_1 \approx i_2 \] (6-36)