Energy Efficient Analysis for WCDMA/3G Homogeneous and Heterogeneous Deployments in Indoor Environment

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Abstract

In near future, the cellular traffic will increase rapidly with majority of the increase coming from Indoor traffic. To cope up with the ever increasing demand, more Base Stations are being deployed in limited areas, which can increase the capacity but will also be responsible for increased energy consumption. Since power is a valuable commodity today both economical and environmental wise, energy efficient deployment along with capacity improvement is crucial for both incumbent and new telecom operators.

The objective of this Thesis is to evaluate Power consumption and Capacity for Indoor users, both in Homogeneous and Heterogeneous infra structure cases for the 3G WCDMA/UMTS technology. The comparison is done for Uniform and Non-Uniform Traffic Distributions. In homogeneous case, results indicate that there is a tradeoff between Area Power Consumption, APC and Area Spectral Efficiency, ASE. Large Macro Base Stations covering a limited Indoor Area use less APC but provides low ASE. Small Micro Base Stations which cover the same Indoor Area consumes little more APC then Macro BS but increases the ASE manifold.

In Heterogeneous case results suggest that Heterogeneous Networks (HETNET) cases enhance the Area Throughput significantly with a small increase in Area Power Consumption. MACRO+10WLAN\(^1\) is the best HETNET case in both Uniform and Non-Uniform Traffic with up to 40\% Energy savings and higher data/user compared to MACRO Only deployment. The traffic patterns, number of active users in a cell and Inter Site Distances between Base Stations strongly influence the energy saving and capacity enhancements.

\(^1\) 10WLAN is a case studied in this report where each Macro cell includes 10WLAN access points. 
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1 Introduction

Today, energy consumption in both developing and developed countries is rapidly increasing day by day. To keep up with the demand of energy, new power projects have to be initiated which are expensive and take a considerable amount of time. Apart from increase in expenditures, new power projects increase the carbon emissions and contribute to the Global Warming. This scenario has forced governments in numerous countries to look for energy efficient solutions in different sectors of society, especially in Information and Communication Technology (ICT).

Telecommunication sector and especially Cellular Networks are parts of ICT that is rapidly expanding throughout the globe. With new technologies like 3G and LTE coming to the market; this sector will grow more in future. Currently, telecommunication sector is consuming around 1-2% of total energy consumption of the world and generates approximately 1% of Carbon Dioxide (CO₂) emissions [1] with percentages expected to rise further.

In Cellular Networks, the prime energy users are Base Stations, backhaul servers and routers. Around 80% energy is consumed by the Base Stations [2]. Because of this statistic, most of the energy saving research has been focused on the Base Station. Researchers have primarily focused on network deployment strategies where low power Micro BS compare to high power Macro BS are used to provide services to the users especially in Indoor scenarios [3].

It is estimated that around 80% of the total cellular traffic is generated Indoors [4]. The wireless infrastructure in Telecommunication networks is mostly situated outdoors with giving mobile services to the users inside the buildings. The main problem with the outdoor network in providing indoor services is signal attenuation, which occurs due to penetration losses as radio signal propagates from outside to inside the building [5]. This scenario might not be energy efficient, compared to a dedicated indoor networks solution.

This Thesis discusses the power consumption and spectral efficiency analysis to cover an Indoor environment by discussing homogenous and heterogeneous Base Station deployments. In homogenous BS deployment, comparisons are done in terms of energy saving for a specific Quality of Service between “Only Macro BS deployment outdoor” and “Only Micro BS deployment indoor”. In addition to that, Heterogeneous BS case is also discussed in which Pico BS and WLAN are added with Macro Base Station. The results are analyzed using simulations and some results are verified by testing and measurements on TEMS.
1.1 Thesis Problem:
The green energy solutions in mobile networks are gaining popularity continuously due to their benefit of low costs and friendly impact on the environment. Most of the traffic generated in cellular network comes from indoor environments especially homes, big shopping plazas and office complexes. The mobile operators generally cover the indoor environment from the macro Base Stations that are installed outside which might be less energy efficient compare to a dedicated indoor network.

The purpose of this Thesis is to investigate and compare the energy consumption of outside macro Base Stations with the dedicated indoor Micro/Pico wireless networks. The thesis works aims to model energy consumption properties of Macro Base Stations versus indoor Micro networks considering the following variables:

- Path Loss Models
- Variable Traffic Demand i.e. 5-50Gbytes user/month
- Frequency Bands. Initially with 3G/UMTS frequency band and optionally with 4G/LTE.
- Test buildings of Electrum and Tax office department in SOLNA (Optional).
- Multiple Indoor Solutions.

1.2 Previous Work and Thesis Motivation:
There has been a lot of research done on the Indoor Solutions for mobile systems but comparatively much less on the energy efficient solutions for indoor environment. Researchers have put effort in analyzing the ways to improve energy efficiency in GSM systems but very few have put same effort on 3G and LTE. This Thesis work will help in understanding the energy efficient properties for above mentioned standards in indoor environments.

Recent research in energy conservation in wireless systems have shown that around 90% of energy is consumed by the operator equipment in a typical wireless network [6]. The prime user of the energy is Base Transceiver Station (BTS) in cellular network which accounts for around 80% of total electrical power consumption [7]. Some of the previous works done in wireless systems energy savings are as follow:

1.2.1 Technische Universitet Dresden (TUD)
TUD has produced number of research papers on the energy efficiency in heterogeneous networks. Linear power models have been used to compare energy efficiency between macro and mini (primarily indoor) networks in different traffic load conditions [8]. The models incorporate the losses from system components including power amplifiers, antennas and A/D convertor. The simulations assume that the users are homogenously distributed in the network with worst case scenario considered i.e. Busy Hour [7].
1.2.2 EARTH Project:
Earth is an EU FP7 project whose main aim is to investigate and propose methods to improve the energy efficiency of a mobile broadband system [9]. The main focus of the EARTH study is Long Term Evolution (LTE) and LTE-Advanced but it is also working on UMTS/3G [9]. EARTH is focusing and developing those technologies, which will help reduce the energy consumption and OPEX of a wireless communication system. In addition to that, it will work on reducing the environmental pollution as well. EARTH is focusing on following path for the implementation of its goals:

- Network Management techniques which are adaptive to load variations
- Energy efficient network architectures
- Efficient Cellular Deployment Strategies
- Radio and resource management protocols [9]

There are several areas that can be optimized for energy efficiency as proposed by the EARTH project. Some of them are:

1.2.2.1 Discontinuous Transmission and Sleep Mode:
The majority of the Base Stations are idle in the time where there is very low traffic on the network. The Base Station can be put in sleep mode during this time which will significantly reduce the energy consumption [10].

1.2.2.2 Power Amplifier:
Power Amplifier in the macro BS consumes most amount of power. PA’s are operating at high DC power and independent of traffic load. This causes a lot of waste in power when there is comparatively low load on the system. The EARTH project proposes to optimize the power efficiency by minimizing the power consumption at different levels. Also power can be saved by deactivation of the PA in specific time slots when there is no transmission [10].

1.2.2.3 Antennas:
The energy efficiency can be achieved in antennas by optimizing it with feeder cable. The metal and dielectric materials with low loss could be investigated for efficient performance.

1.2.3 Royal Institute of Technology (KTH):
There is currently a lot of work going on the energy efficiency domain in wireless systems in KTH. Research is going on the power consumption properties in heterogeneous networks with the help of predefined models and simulations [11].

A master thesis on energy aspects of 2G and 3G technologies was completed by a student in KTH a couple of years ago [12]. The thesis gives insight about the power consumption of different components of a wireless network and then gives some recommendations on energy saving techniques. A Wireless Network Project about “Power savings in Heterogeneous Networks” was done by students in KTH last year [13]. That project gave recommendations for
energy efficient deployment of Base Stations for different QoS scenarios. The results showed that HETNET's are much more power efficient than traditional Macro deployments.

2 General Background

2.1 WCDMA

Wideband Code Division Multiple Access (WCDMA) is a 3rd Generation Wireless standard that uses Direct-Sequence Code Division Multiple Access (DS-CDMA) technique [14]. The Uplink frequency band in WCDMA is in the range from 1920 to 1980 MHz, while the Downlink frequency band is between 2110 to 2170 MHz [15]. The most common Bandwidth used by WCDMA currently is 5MHz and can offer data rates up till 10Mbps [14]. Some of the specifications that are used in Thesis Simulations for WCDMA are given in the “Appendix A”.

2.2 Indoor Coverage Background

2.2.1 Dedicated Indoor Solutions so called DAS systems:

In order for dedicated indoor solutions to work properly in terms of coverage and capacity, the indoor cells should be able to distribute uniform signal throughout the building with the help of Distributed Antennas [4]. The two most common kinds of Distributed Antenna Systems (DAS) are Active DAS and Passive DAS. Both Antenna Systems have advantages and disadvantages according to the situation and technology in use.

2.2.1.1 Active DAS:

Active DAS uses optical fibers and cables for the interconnection of active end node RF components. The active DAS systems are able to balance out the effects of attenuation and distance of the cables. Active DAS solutions require less downlink power from Base Station because of the presence of Remote Unit (RU) close to the Antenna System. The BS transmitter power requirement for active DAS is around 10dBm. This amount of power can be feed from a small Base Stations, made of comparatively mini components emitting negligible amount of heat. This means that there is no need for cooling systems for active DAS, which helps in reducing Operational Expenditure (OPEX) and is more eco friendly. This helps in conservation of valuable energy and is a step forward towards “Green Solutions” [4].

2.2.1.2 Passive DAS:

Passive DAS is the most common DAS used in mobile services today, and build on splitters, coax cables and antennas. The design procedure of passive DAS is easily understandable but it is a time consuming process. Passive DAS can work in harsh environmental conditions and its components are easily available in the market. One of the draw backs of Passive DAS is that there is no mechanism for error detection in system. Also it requires high power Base Station and
dedicated equipment for site support. The high losses in the cables also affect the performance of the system [4].

2.2.2 Indoor Coverage from Micro/Pico Base Stations
Micro and Pico Base Stations are low power and small nodes compare to Macro Base Stations. These are primarily used in indoor environments where there is high traffic load for providing high capacity. To cover an indoor environment from only Micro/Pico BS, the number of Micro/Pico BS required are comparatively higher then Macro BS because of less range and transmitting power of the Micro BS, but power consumed by a Micro/Pico BS is much lower than corresponding Macro BS. This scenario could be helpful in energy efficiency gains as for a fixed quality of service (coverage and capacity), Micro/Pico BS could be performing better then Macro BS in terms of power used.

2.2.3 Indoor Coverage from Macro Base Station’s Point of View:

![Diagram](https://example.com/diagram.png)

Fig 2.1: Indoor Coverage from Outside Macro Network [3]

Figure 2.1 shows a common way of providing indoor cellular coverage from outside the building. This scenario has some pros and cons in terms of energy efficiency with some of them discussed below:

1. The signal from outside wireless antenna will require a lot more power compared to a dedicated indoor antenna as there would be considerable loosens due to Free Space Non Line of Sight (NLOS) Propagation up to, and Penetration Losses from the building. Modern buildings increase the penetration loosens more due to presence of thick material in the walls and metalized windows [5].
2. In 3G networks, power load per user (PLPU) is an important factor to consider due to the direct relationship between the capacity and downlink power of the Base Station. This means that more the PLPU, greater will be the capacity required from the Base Station. In outdoor macro networks, base stations have to overcome the penetration losses for indoor coverage and in effect will have to transmit more power. This situation will increase the capacity required from the outdoor Base Station which ultimately will result in an increase cost for indoor traffic [4].

3. If there is more than one Base Station covering the building from outside, the signal strength is generally at acceptable levels. However, in UMTS this can be a problem due to the presence of Soft Handovers. In Soft Handovers, one mobile can be simultaneously communicating with all cells and thus putting load on all the macro networks. This increases the OPEX of the cellular system [4].

4. The power consumption of Macro Base Stations is no doubt higher than the Pico Base Stations. To cover inside of a building from outside wireless networks, there would be comparatively less Base Stations required than covering the building from dedicated indoor solutions [12]. The installation of additional indoor Base Stations will increase the Capital Expenditure (CAPEX) for the operator.
2.3 Heterogeneous Network (HETNET)

Fig 2.2: HETNET Scenario [16]

In Wireless networks, Heterogeneous Networks are those networks which are composed of both Macro BS and small power Pico or WLAN nodes as shown in figure 2.2. These small power Pico/WLAN nodes are used with traditional Macro BS to provide enhanced capacity and higher data rates to end users in hotspots areas such as Indoor Offices and Malls.

2.4 Propagation Models:
Path loss is the loss of the signal power as the signal travels between a transmitter and receiver. This power loss is due to the attenuation of signal in free space, absorption, scattering and refraction [17]. For indoor propagation from Macro Base Stations, a variety of models have been specified which consider different indoor environments. Not a single model is a standard for all indoor buildings and a particular model is selected considering all the aspects of an indoor test environment. Some of the most common indoor models used today are:

2.4.1 The COST 231/ Walfish-Ikegami model for MICRO Cell Area:
This model is developed for non Line of Sight (LOS) urban environment [18]. Model parameters are:

- Carrier Frequency(MHz)
- Building Separation(m)
- Building Height(m)
• Width of Road (m)
• Road Orientation(degrees)

2.4.2 Log-Distance Path Loss Model:
This model is used to calculate the path loss a signal experiences inside an indoor location [19].

The model can be shown as:

\[ PL(dB) = PL0 + 10 \cdot Y \cdot \log_{10} \frac{d}{d_0} + Xg \] (2.1)

\( PL(dB) \) = Total path loss

\( PL0 = \) Path Loss at reference distance

\( Y = \) Path Loss exponent

\( Xg = \) Normal random variable

2.4.3 Outdoor Path Loss Model NLOS 3GPP (Suburban MACRO)
This model has been developed by 3GPP using different measurement results and literature. The model can be applied in the frequency range from 2-6GHz and multiple antenna heights [20].

The Model is given as:

\[ PL(dB) = 161.04 - 7.1 \cdot \log_{10}(W) + 7.5 \cdot \log_{10}(h) - \left( 24.37 - 3.7 \cdot \left( \frac{h}{hBS} \right) \cdot 2 \right) \log_{10}(hBS) + \left( 43.42 - 3.1 \cdot \log_{10}(hBS) \right) \left( \log_{10}(d) - 3 \right) + 20 \cdot \left( \log_{10}(f) - \left( 3.2 \cdot \left( \log_{10}(11.75 \cdot hUT) \right) \right) \right) 2 \cdot 4.97 \] (2.2)

\( PL(dB) \) = Total path loss

\( d = \) Distance in meters (10-5000m)

\( W = \) street width (5-50m)

\( h = \) Average Building Height (5-50m)

\( hBS = \) Base Station Height (10-150m)

\( hUT = \)Height User Terminal (1-10m)

\( f = \) Frequency (2-6GHz)

Standard Deviation = 8
2.5 Only Indoor Propagation Models (Propagation within Buildings):

For Micro/Pico Base Stations that are placed Indoors, Empirical and Statistical models are used for Path Loss Calculations. Few models are given below:

2.5.1 The Indoor Path Loss Slope (PLS) Model:
A common method for calculating the path loss in different environments is the PLS model. Numbers of measurements are taken for path loss at different distances from the antenna and in the end a path loss slope is made [4].

\[ PL(dB) = PL(d0) + 10 \times n \times \log(d) \]  

(2.3)

Where the \( PL(d0) \) is the path loss that is measured at 1m distance which is given by \((32.5 + 20\log(f) + 20\log(d)) \) where \( n \) is the PLS coefficient \( n \) is different for different indoor Environments. [4]

2.5.2 Wall and Floor Factor Models (Empirical Models):

Characterize Indoor Path loss by:

A fixed exponent of 2 (as in free space) + additional loss factors relating to Number of floors \( n_f \) and walls \( n_w \) intersected by the straight-line distance \( r \) between terminals \[21\] [4].

\[ LT = L1 + 20 \times \log_{10}(r) + nf \times af + nw \times aw \]  

(2.4)

\( af \) = Attenuation Factor per floor

\( aw \) = Attenuation Factor per wall

\( L1 \) = Reference path loss at \( r=1m \).

2.5.3 Wall and Floor Factor Models (ITU-R Models):

This model has the similar approach as above mentioned Wall and Floor Loss Model but in this case floor loss is count explicitly and loss between points on the same floor included implicitly by changing path loss exponent.

\[ LT = 20 \times \log_{10} fc [MHz] + 10 \times n \times \log_{10} r [m] + Lf \times nf - 28 \]  

(2.5)

Here \( n \) is different for different environments and carrier frequency. For example \( n \) is 3 for office environment at frequency range 1.8-2.1GHz \[21\].
Similarly \( L_\text{nf} \) is \( 15+4 (n_f - 1) \) in indoor office environment for frequency range 1.8-2.1GHz.

### 2.5.4 Path Loss Model WINNER (Indoor MICRO)

This Path Loss Model has been developed by WINNER for Indoor propagation scenario. This Model can be used in frequency range 2-6GHz and for different antenna heights [22].

Model is given as:

\[
PL(dB) = 36.8 \times \log10 (d[m]) + 43.8 + 20 \times \log10 \left( f_c \left( \frac{GHz}{5} \right) \right) + X
\]  

(2.6)

\( d = \) Distance between transmitter and receiver

\( f_c = \) Frequency (2-6GHz)

\( X = 5(n_w - 1) \) \( n_w \) is the number of walls indoor between UE and BS.

Standard Deviation = 4

### 2.6 Area Power Consumption (APC)

Area power consumption (APC) is used to measure the power consumption of a network relative to its Area. It is defined as the average power consumption per cell divided by the cell area and is measured in Watts per square kilometer [7] [8]. APC can be expressed mathematically as:

\[
APC = \frac{PCell}{ACell}
\]  

(2.7)

Here \( PCell \) is the total Power consumed by a Macro or Micro Base Station and \( ACell \) is the Area of the corresponding Cell [23] [3].

### 2.7 Spectral Efficiency

Spectral efficiency is optimized used of spectrum so that maximum amount of information can be transmitted in a given bandwidth as a function of available signal to noise ratio. In the simulations below, Shannon’s equation have been used to attain maximum spectral efficiency [24]:

\[
Spectral \ Efficiency = \log2 \left( 1 + \frac{S}{N} \right)
\]

\( S/N \) is in ratio
2.8 Area Spectral Efficiency (ASE)

The Area Spectral Efficiency can be defined as the mean of the achievable rates in a network per unit Bandwidth per unit Area. It is measured in bits per second per hertz per square kilometer [23]. Since Hertz is the inverse of the second, it is correct to express ASE in bits/km² [25]. Mathematically Area Spectral Efficiency can be expressed as:

\[
S = \left( \frac{1}{A_{\text{Cell}}} \right) \cdot E[S(X)] = \frac{1}{A_{\text{Cell}}} \int A S (X = x) \, dx
\]  

Where \( S (X = x) \) is the ASE of the user \( x \) and \( A_{\text{Cell}} \) is the Area of the Cell. \( E[S(X)] \) shows that average of Spectral Efficiencies have been taken. Thus ASE is the mean of all the users in the system divided by the Cellular Area and it would be different from individual data rates [25] [26].

2.9 Quality of Service (QoS)

Quality of Service is used to analyze the network performance. In Wireless systems, QoS can be defined as providing a certain Coverage and Data Rates to all the users in the Wireless network.
3 Methodology

3.1 Rudimentary Network Emulator (RUNE):

The simulations are performed in MATLAB program of RUNE. Rune is now days an Open source program but it used to be available for the KTH students and owners of [27] only. This tool was developed by Magnus Almgren, at that time, working in Ericsson and it consists of multiple functions that can be used to simulate cellular networks. Numerous cellular system aspects like creation of cells, base stations locations, channel assignment, propagation losses, interferences, shadowing and mobility can be easily handled by the functions used in RUNE [35]. However, RUNE does not provide all functionalities necessary and therefore new scripts have been added for modeling of CDMA systems according to the requirements of this Thesis. RUNEFC (Basic Dynamic Simulation Function for CDMA) is a function defined in RUNE for the simulations to be performed in WCDMA environment. RUNEFC is being used for simulations in this Thesis.

3.2 TEMS

TEMS is a software first developed by Ericsson for the purpose of Monitoring, Measurement, Analysis and Verification of Cellular Networks. Since a few years TEMS products are owned and developed by ASCOM, they have provided full support and help regarding the TEMS Software [28]. Figure 3.1 shows measurements set up including a 3G TEMS investigation phone (Sony Ericsson Z750i) and a USB code key that contains valid license is attached to the laptop.

Fig 3.1: ASCOM TEMS tool kit interfaced with PC acts as a measurement transceiver unit [31]
3.3 Thesis Methodology:
Energy Consumption models are implemented in RUNE (MATLAB) with measurements performed with TEMS/3G software to verify some of the simulations.

3.3.1 Scenario
The basic requirement of this Thesis is to investigate energy efficiency savings for Indoor environment in Homogenous and Heterogeneous deployments versus “classical” Macro cell systems. The user distribution is divided in two cases, i.e. Uniform Distribution of the users and Non-Uniform Distribution of the users. In the Uniform Distribution users are evenly distributed in the Cellular Area while in Non-Uniform Distribution, Hotspots have been introduced to distribute users non-uniformly as shown in fig 3.2 and fig 3.3. Note that, it is assumed that all the users in this investigation are Indoors.

Fig 3.2: 3 Hotspots with 50% of total users           Fig 3.3: Uniform Traffic Distribution

The simulation parameters including Path loss models, Power models and calculation of ASE, APC as defined in Chapter 2.6 and Chapter 2.8 have been based on 3GPP standards and IEEE research papers.

3.3.2 Approach
The simulations are performed in RUNE and used WCDMA as the Access Technology. The simulations are done in Busy Hour (BH) and non-Busy Hour scenarios. Busy Hour is typically the hour of the day when the cellular traffic is at its peak i.e. largest numbers of calls are made [29]. The approach followed in investigations for comparison of different scenarios is as follow:

1. Energy Efficiency simulation for Uniform Traffic Distribution in Homogenous Deployments
2. Energy Efficiency simulation for Non-Uniform Traffic Distribution in Homogenous Deployments
3. Energy Efficiency simulation for Uniform and Non-Uniform Traffic Distribution in Heterogeneous Deployments

4. Measurements using TEMS Software

Firstly, the energy efficiency evaluation is done in a uniform traffic distribution scenario. In this scenario, Only Macro BS deployment is compared with Only Micro BS deployment for a certain QoS in an indoor environment. Two traffic profiles Busy Hour and Non-Busy Hour are simulated.

In the second phase, above mentioned procedure is repeated but for Non-Uniform traffic Distribution. For Non-Uniformity, Hotspots have been introduced. The amount of users and the number of hotspots can be changed through functions defined in RUNE (MATLAB).

In the third phase, Heterogeneous Networks have been added to compare the Energy Efficiency for Uniform and Non-Uniform Traffic Distribution. In this scenario, Pico Base Stations and WLAN’s have been added with the Macro Base Stations. The power consumptions of HETNET’s for different QoS requirements have been analyzed and compared with Homogenous Deployments for BH and NBH traffic load.

Finally, an average measured value have been taken in the Electrum 1 Building (Isafjordgatan 22-26, Kista, Stockholm) to compare the result with the simulations.
3.4 Simulations

The Simulation work was started by understanding the RUNE code (MATLAB). The code in RUNE is very general and can achieve very limited objectives. To cover the scope of this thesis, functions and change were added to some parts of the RUNE code to get the desired results. The functions added in the RUNE were calculations of Area Spectral Efficiency for both Uniform and Non-Uniform Distributions of traffic, estimation of Power Consumption of Only Macro, Only Micro, HETNET Sites and computation of Area Throughput.

The important changes in the RUNE code were the parameters setting for each site type, addition of specific Propagation Models, Power Models, addition of Hotspots to accommodate the Non-Uniform Traffic Distribution case and Handoff Management.

3.4.1 Network Model for Simulation:
The network model used in the simulation is hexagonal grid structure of side length $R$, Inter site distance $D=\sqrt{3}R$ and Area $A_c=3\sqrt{3}/2 \ R^2$. The Macro Base Stations are placed in the middle of the cell structure propagating in Omni directional way. For the Homogeneous case in Indoor scenario, Macro sites are placed outside using Wrap around technique\textsuperscript{2} to cover an Indoor area. Similarly, to cover the same Area from Inside, Micro Sites are placed in an Inside environment for comparison between Data Rates and Power Consumption in Homogeneous situation. 3 Macro BS and 12 Micro BS are considered in homogenous scenario to cover same Indoor Area.

3.4.2 Propagation Models for Simulation:
The propagation models used in the MATLAB simulations for different scenarios are given as:

3.4.2.1 Outdoor to Indoor Propagation:
In the case where only Macro BS are placed outside, Path Loss in eq. 2.2 has been used. The model is 3GPP defined and valid for suburban scenarios. The model considers shadow fading and log normal fading in its calculations. Because the signal propagates from outside to inside, a fixed Attenuation of 15dB has been added in every link from BS to the user. The model used for signal propagation by considering different parameter is given as:

$$\text{PLNLOS} = 39.08 \times \log_{10} (d) + 12.8489 + \text{Wall loss}$$

(3.1)

Non-Line of Sight case is discussed here. The simulation parameters are defined in detail in Appendix C.

3.4.2.2 Indoor Propagation:
In this case where only Micro BS are placed inside, Propagation Model equation 2.2 has been used. This model has been developed using studies from literature and extensive simulations in Indoor by WINNER Project [22]. This model is used after putting different parameter values in equation 2.6.

\textsuperscript{2} Wrap Around Technique is used to take care of co-channel interference in a cellular network. It is implemented by default in RUNE
\[ PL = 36.8 \log_{10}(d) + 36.265 + X \]  

(3.2)

\( X \) is Attenuation of Walls Indoor between BS and Mobile Station given by: \( X = 5n_w - 1 \), where \( n_w \) is number of walls Indoor.

The parameter values are defined in detail in Appendix C.

### 3.4.3 Power Models

Current state of the art technology is used here.

#### 3.4.3.1 Homogeneous Case:

**Macro Only**

The power models have been selected from [23] in both homogeneous and heterogeneous cases for WCDMA deployment. The power model for Macro BS described in [23] has a linear relationship between Average Radiated power per site and Average power Consumption. The relationship is as follow:

\[ P_{macro} = A_{macro} \cdot P_{tx} + B_{macro} \]  

(3.3)

The coefficient \( A_{macro} \) here takes into account the efficiency of amplifiers and losses caused by feeders and cooling of sites. The coefficient \( B_{macro} \) is independent of the average power transmitted and models the power consumed in signal processing, battery backup and as well as site cooling [30]. Both these coefficients are constant for Macro BS. The power model is calculating average power consumption with respect to average transmit power \( P_{TX} \), this assumption is valid because currently deployed Macro sites power consumption rarely depends upon the traffic load [23]. The value of \( P_{tx} \) is calculated using path loss equation 2.2.

Area Power Consumption of One Macro cell is calculated as:

\[ APC = P_{macro} / \text{AreaCell} \quad (\text{Watt/km}^2) \]  

(3.4)

The simulation parameters are described in Appendix B.

**Micro Only**

The power model for Micro BS is given as:

\[ P_{micro} = L \cdot (A_{micro} \cdot P_{tx} + B_{micro}) \]  

(3.5)

The coefficients \( A_{micro} \) and \( B_{micro} \) have the same analogy as \( A_{macro} \) and \( B_{macro} \). Here parameter \( L \) models the activity level of the BS. This is advantageous since now power consumption is dependent on the load served by the device. In heavy traffic scenario, \( L \) will be close to 1 while in low traffic scenario, Load will be close to 0 [23]. The value of \( P_{tx} \) is calculated using path loss equation 2.6. The results of power consumption are compared in terms of Area Power Consumption. APC is defined in equation 1.
Area Power Consumption of **One Micro cell** is calculated as:

\[ APC = \frac{P_{micro}}{Area_{cell}} \quad (\text{Watt/km}^2) \]

The simulation parameters that are used for power consumption analysis are described in Appendix B Table B.1.

3.4.3.2 **Heterogeneous Case:**
In Heterogeneous case, the power consumption equation is given as:

\[ P_{hetnet} = P_{macro} + N \times P_{pico/WLAN} \quad (3.6) \]

Here \( P_{macro} \) is the power Consumed by Macro BS as given in equation 3.4, \( N \) is the number of Pico/Wlan BS and \( P_{pico/WLAN} \) is power consumed by Pico or WLAN BS depending on the coefficients A and B. For \( P_{pico/WLAN} \) calculations, equation 3.5 has been used.

Area Power Consumption is calculated as:

\[ APC = \frac{P_{hetnet}}{Area_{cell}} \quad (\text{KWatt/km}^2) \quad (3.7) \]
4 Results
The simulations have been performed for different homogeneous cases. The results and analysis of the different Simulation Scenarios are discussed in detail below:

4.1 Uniform Traffic Distribution Homogeneous
In uniform traffic distribution, the users are distributed uniformly around the desired area as shown in figure 3.3. The Area Spectral Efficiency is calculated using equation 2.9. The Base Station parameters are described in detail in Appendix B and Appendix C.

4.1.1 Busy Hour
The Busy Hour is the time of the day with peak traffic. In BH scenario, load of 150 active users have been considered. 3 Macro sites and 12 Micro sites have been chosen in homogeneous case, so the load comes out to be 50 active users/site (Macro) and around 13 active users/site (Micro) respectively. Inter site Distance for Macro sites ranges from 400m-1600m while for Micro sites it ranges from 200m-600m. The Area Spectral Efficiency in bits/sec/Hz/km² against Inter Site Distance (ISD) in meters is given below:

![Area Spectral Efficiency vs. Intersite Distance](image)

**Figure 4.1 ASE vs.ISD for Uniform Distribution Busy Hour (Homogeneous)**

---

3 In Kista on Average 10000 Users (BH) in 1 km² divided between 4 Telecom Operators i.e. Telia, Telenor, 3 and Tele2. 10000 users further divided into 3 technologies GSM, 3G and LTE. This comes out to be around 900 users for 3G per operator in 1 km². At Busy Hour, 20-30% Active Users in a system, that’s why 150 value chosen.
The simulation results are logical and similar to the results in literatures [3][8][23][25]. The result shows that micro BS provides higher ASE for a certain range of Inter Site Distance than macro BS in Indoor traffic.

4.1.2 Non-Busy Hour:
The non-BH is the time of the day with comparatively very less load then BH. In non-BH scenario, load of 30 active users have been considered. 3 Macro sites and 12 Micro sites in homogeneous case have been chosen, so the load comes out to be 10 active users/site (Macro) and around 3 active users/site (Micro) respectively. Inter site Distance for Macro sites ranges from 400m-1600m while for Micro sites it ranges from 200m-600m. The ASE in bits/sec/Hz/km² against ISD is given below:

![Figure 4.2 ASE vs.ISD for Uniform Distribution NON-Busy Hour (Homogeneous)](image)

In Non-BH, ASE is relatively higher then BH because of less load on BS and more resources available to BS.
4.2 NON-Uniform Traffic Distribution Homogeneous

In NON-uniform traffic distribution, the users are distributed non-uniformly around the desired area as shown in figure 3.1. The HotSpots are introduced to produce non-uniformity in the distribution of users. The number of Hotspots and the users that are residing in the HotSpots region can be changed according to the requirements.

4.2.1 Busy Hour

In Non-Uniform Distribution, Busy Hour and Non-BH cases have been considered. In BH scenario, load of 150 active users have been considered. Inter site Distance for Macro sites ranges from 400m-1600m while for Micro sites it ranges from 200m-600m. Number of HotSpots introduced for the simulation purposes are 4. 50% of the total users are residing in the Hotspots while the rest of them are outside the Hotspot zone. The ASE in bits/sec/Hz/km² or bits/km² against ISD in meters is given below:

![Area Spectral Efficency vs. Intersite Distance](image)

**Figure 4.3 ASE vs.ISD for Non-Uniform Distribution Busy Hour (Homogeneous)**

In Non-uniform case, data rates are lower than the data rates of uniform distribution. This is logical as there might be some areas where there is lot of concentration of users and much load on the BS there but other Base Stations will be more or less idle, thus contributing to low average ASE.
4.2.2 Non-Busy Hour:
In non-BH scenario, load of 30 active users have been considered. Inter site Distance for Macro sites ranges from 400m-1600m while for Micro sites it ranges from 200m-600m. Hotspots are 4 with 50% users in Hotspots area. The ASE in bits/sec/Hz/km$^2$ against ISD is given below:

![ASE vs. ISD for Non-Uniform Distribution Non-Busy Hour (Homogeneous)](image)

**Figure 4.4 ASE vs.ISD for Non-Uniform Distribution Non-Busy Hour (Homogeneous)**

In Non-BH case for non uniform traffic distribution, the ASE is lower.
4.3 Area Power Consumption:
The Area Power Consumption has been calculated using formulas 2.2, 2.6 and 2.7. In the calculation of Micro BS Power; Assumed Load to be 0.75, 0.5 and 0.25.

![Area Power Consumption](image)

**Figure 4.5: Area Power Consumption (Homogeneous Case)**

The figure shows that APC for both Macro and Micro deployments (all) has minima with respect to the Inter site Distance. The ISD where lowest Power Consumption for Macro, Micro BS (0.25 Load), Micro BS(0.5 Load) and Micro BS(0.75 Load) is at 1260m, 380m, 380m and 380m respectively. It is recognized that 95% Coverage is assumed in every scenario.

4.4 Simulation Results and Analysis:
The above simulation results give an idea about how the ASE and APC are dependent on the ISD, BS type and users distribution. The approach followed in the analysis of the results is the same as of [23], [3], [8] and [25]. There are two-three different targets of ASE that will be analyzed to get a better picture. The ASE targets for BH are 3 bits/sec/Hz/km$^2$, 6 bits/sec/Hz/km$^2$ and 10bits/sec/Hz/km$^2$ while for Non-BH are 3 bits/sec/Hz/km$^2$ and 6 bits/sec/Hz/km$^2$. Next the corresponding ISD’s at which these targets are met were calculated and compared with the ISD’s that gave the minimum APC to find optimum distance [13]. The
optimum distance is the distance where target ASE is achieved and also the APC is the minimum that we get from a range of APC values. The network deployment is selected based on the minimum APC for a targeted ASE. For BH 0.5 Load Micro APC graph have been chosen while for Non-BH, 0.25 Load APC graph is considered.

### 4.4.1 Area Spectral Efficiency Target 10bits/sec/Hz/km$^2$ for BH Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved(m)</th>
<th>Minimum APC distance(m)</th>
<th>Power Consumption at Minimum APC distance(kWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance(kWatt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>440</td>
<td>7.510</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>7.334</td>
<td>380</td>
<td>7.334</td>
</tr>
</tbody>
</table>

For a target of 10 bits/sec/Hz/km$^2$ in BH Uniform Traffic Distribution, Table shows that Micro Only deployment is better for energy efficiency.

### 4.4.2 Area Spectral Efficiency Target 6bits/sec/Hz/km$^2$ for BH Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved(m)</th>
<th>Minimum APC distance(m)</th>
<th>Power Consumption at Minimum APC distance(kWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance(kWatt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>560</td>
<td>4.756</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>7.334</td>
<td>380</td>
<td>7.334</td>
</tr>
</tbody>
</table>

For a target of 6 bits/sec/Hz/km$^2$ in BH Uniform Traffic Distribution, Table shows that Macro Only deployment is better for energy efficiency.
4.4.3 Area Spectral Efficiency Target 3bits/sec/Hz/km\(^2\) for BH Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved (m)</th>
<th>Minimum APC distance (m)</th>
<th>Power Consumption at Minimum APC distance (KWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>650</td>
<td>3.648</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>7.334</td>
<td>380</td>
<td>7.334</td>
</tr>
</tbody>
</table>

For a target of 3 bits/sec/Hz/km\(^2\) in BH Uniform Traffic Distribution, Table shows that Macro Only deployment is better in power consumption.

4.4.4 Area Spectral Efficiency Target 6bits/sec/Hz/km\(^2\) for NON-BH Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved (m)</th>
<th>Minimum APC distance (m)</th>
<th>Power Consumption at Minimum APC distance (KWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>600</td>
<td>4.197</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>3.667</td>
<td>380</td>
<td>3.667</td>
</tr>
</tbody>
</table>

For a target of 6 bits/sec/Hz/km\(^2\) in NON-BH Uniform Traffic Distribution, Table shows that Micro Only deployment is better with optimum ISD 380m.
### 4.4.5 Area Spectral Efficiency Target 3bits/sec/Hz/km² for NON-BH Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved (m)</th>
<th>Minimum APC distance (m)</th>
<th>Power Consumption at Minimum APC distance (kWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance (kWatt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>840</td>
<td>2.459</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>3.667</td>
<td>380</td>
<td>3.667</td>
</tr>
</tbody>
</table>

For a target of $3 \text{ bits/sec/Hz/km}^2$ in NON-BH Uniform Traffic Distribution, Table shows that **Macro Only** deployment is better with optimum ISD at 840m.

### 4.4.6 Area Spectral Efficiency Target 6bits/sec/Hz/km² for BH NON-Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved (m)</th>
<th>Minimum APC distance (m)</th>
<th>Power Consumption at Minimum APC distance (kWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>480</td>
<td>6.350</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>7.334</td>
<td>380</td>
<td>7.334</td>
</tr>
</tbody>
</table>

For a target of $6 \text{ bits/sec/Hz/km}^2$ in BH NON-Uniform Traffic Distribution, Table shows that **Macro Only** deployment is more energy efficient.
### 4.4.7 Area Spectral Efficiency Target 3bits/sec/Hz/km² for BH NON-Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved(m)</th>
<th>ISD at which Minimum APC (m)</th>
<th>Power Consumption at Minimum APC distance(KWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance(Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>780</td>
<td>2.726</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>7.334</td>
<td>380</td>
<td>7.334</td>
</tr>
</tbody>
</table>

For a target of 3 bits/sec/Hz/km² in BH NON Uniform Traffic Distribution, Table shows that **Macro Only** deployment is better with optimum ISD at 780m.

### 4.4.8 Area Spectral Efficiency Target 6bits/sec/Hz/km² for NON-BH NON-Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved(m)</th>
<th>ISD at which Minimum APC (m)</th>
<th>Power Consumption at Minimum APC distance(KWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance(Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>520</td>
<td>5.458</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>3.667</td>
<td>380</td>
<td>3.667</td>
</tr>
</tbody>
</table>

For a target of 6 bits/sec/Hz/km² in NON-BH NON-Uniform Traffic Distribution, Table shows that **Micro Only** deployment consumes less power.
4.4.9 Area Spectral Efficiency Target 3bits/sec/Hz/km² for NON-BH NON-Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved (m)</th>
<th>ISD at which Minimum APC (m)</th>
<th>Power Consumption at Minimum APC distance (KWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>760</td>
<td>2.833</td>
</tr>
<tr>
<td>Micro Only</td>
<td>200</td>
<td>380</td>
<td>3.667</td>
<td>380</td>
<td>3.667</td>
</tr>
</tbody>
</table>

For a target of $3 \text{ bits/sec/Hz/km}^2$ in NON-BH NON-Uniform Traffic Distribution, Table shows that **Macro Only** deployment consumes less power.
4.5 Area Power Consumption (minimum) VS Area Throughput (Homogeneous):

Area Throughput is calculated by multiplying ASE with 5MHz (3G) bandwidth. For calculation of minimum APC, the same procedure has been used as defined in section 4.4 i.e. optimizing the ISD in terms of APC for different Area Throughput targets.

![Minimal Area Power Consumption vs Area Throughput Targets](image)

**Fig. 4.6 APC (minimum) VS Area Throughput BH (Uniform Traffic Distribution Indoor)**

The above figure shows APC (minimum) vs Area Throughput for uniform traffic distribution scenario (homogeneous). From the figure it is clear that for Throughput targets of less than 50Mbps/km², **MACRO Only** is a better solution in terms of APC but when Throughput targets increase above 50Mbps/km², **MICRO Only** comes to be better in energy efficiency. Figure 4.6 show that MACRO cannot achieve throughput of more than 60Mbps/km².

4.6 Simulation Results (Heterogeneous Cases)

The simulations have been performed for different heterogeneous cases similar to the homogeneous. In the heterogeneous scenario, I am using 4 cases to compare ASE with APC in Indoor environment for different QoS requirements. These cases are ‘**Macro Only**’, ‘**Macro+3Pico**’, ‘**Macro+5Pico**’ and ‘**Macro+10WLAN**’. The number of Pico and WLAN BS
have been motivated by the literature [23][3][25] studies. The positions of the Pico/WLAN BS with respect to Macro BS are shown in sample figure below:

\[ \text{Fig 4.7 HETNET Layout Example} \]

The Base Station parameters are described in Appendix B and Appendix C. The results and analysis of the different Simulation circumstances are discussed in detail below.

\section*{4.7 Uniform Traffic Distribution Heterogeneous}

In uniform traffic distribution, the users are distributed uniformly around the desired area as shown in figure 3.2. The Area Spectral Efficiency for different HETNET cases are calculated using formula 2.9.

\subsection*{4.7.1 Busy Hour}

The Busy Hour is the time of the day with peak traffic. In BH scenario, load of 200 active users\(^4\) have been considered. 3 Macro sites have been chosen with HETNET cases described above. Inter site Distance ranges from \textbf{500m-1700m}. The Area Spectral Efficiency in bits/sec/Hz/km\(^2\) against ISD in meters is given below:

\[ \text{In Kista on Average 10000 Users (BH) in 1 km}^2 \text{ divided between 4 Telecom Operators i.e. Telia, Telenor, 3 and Tele2. 10000 users further divided into 3 technologies GSM, 3G and LTE. This comes out to be around 800 users for 3G per operator in 1 km}\(^2\). At Busy Hour, 25% Active Users in a system assumed, that’s why 200 value chosen.} \]

\(^4\) In Kista on Average 10000 Users (BH) in 1 km\(^2\) divided between 4 Telecom Operators i.e. Telia, Telenor, 3 and Tele2. 10000 users further divided into 3 technologies GSM, 3G and LTE. This comes out to be around 800 users for 3G per operator in 1 km\(^2\). At Busy Hour, 25% Active Users in a system assumed, that’s why 200 value chosen.
Figure 4.8 ASE vs.ISD for Uniform Distribution Busy Hour (Heterogeneous)

The result shows that **Macro+5Pico** gives the highest ASE in Uniform Traffic compared to other HETNET cases but the power consumption of **Macro+5Pico** is also the highest.

### 4.8 NON-Uniform Traffic Distribution Heterogeneous

In NON-uniform traffic distribution, the users are distributed non-uniformly around the desired area as shown in figure 3.3. The stationary HotSpots are introduced to produce non-uniformity in the distribution of users.

#### 4.8.1 Busy Hour

In Non-Uniform Distribution, Busy Hour case has been considered only. Load of 200 users have been considered. 3 Macro sites have been chosen with HETNET cases described above. Number of HotSpots introduced for the simulation purposes are 5. 50% of the users are residing in the Hotspots while the rest of them are outside the Hotspot zone. The positions of the BS are such that Macro BS are placed Outdoors while Pico/WLAN are placed Indoors. The Path Loss Model used for Macro BS is 3.1 while for Pico/WLAN is 3.2. Inter site Distance ranges from 400m-1600m. The Area Spectral Efficiency in bits/sec/Hz/km² against ISD in meters is given below:
The result shows that *Macro+10WLAN* gives the highest ASE in NON-Uniform Traffic compared to other HETNET cases.
4.9 Area Power Consumption (HETNET):
The Area Power Consumption has been calculated using formulas 3.6 and 3.7. Load is assumed to be 1 in all HETNET cases. The simulation parameters used for calculation of APC has been given in Appendix B Table B.1.

![Figure 4.10: Area Power Consumption HETNETs vs ISD (m)](image)

The figure shows that APC for HETNET deployment has minima with respect to the Inter site Distance. The ISD where lowest Power Consumption for ‘Only Macro’, ‘Macro+3Pico’, ‘Macro+5Pico’ and ‘Macro+10WLAN’ occurs at 1260m, 1360m, 1420m and 1340m respectively. 95% Coverage is assumed in all the cases.

4.10 Simulation Results and Analysis:
There were two different targets of ASE that were analyzed to get a better picture. The ASE targets are 3 bits/sec/Hz/km² and 6 bits/sec/Hz/km² respectively. Next the corresponding ISD’s at which these targets are met were calculated and compared with the ISD’s that gave the minimum APC to find optimum distance [13]. The optimum distance is the distance where target ASE is achieved and also where the APC is the minimum that we get from a range of APC values. The network deployment is selected based on the minimum APC for a targeted ASE.
### 4.10.1 Area Spectral Efficiency Target 3bits/sec/Hz/km² for BH Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved(m)</th>
<th>Minimum APC distance(m)</th>
<th>Power Consumption at Minimum APC distance(kWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance(kWatt)</th>
<th>% of Power Saving compare to Macro Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>500</td>
<td>1260</td>
<td>1.844</td>
<td>820</td>
<td>2.540</td>
<td>0</td>
</tr>
<tr>
<td>Macro+3Pico</td>
<td>500</td>
<td>1360</td>
<td>2.136</td>
<td>1240</td>
<td>2.172</td>
<td>14.5</td>
</tr>
<tr>
<td>Macro+5Pico</td>
<td>500</td>
<td>1420</td>
<td>2.309</td>
<td>1420</td>
<td>2.309</td>
<td>9.1</td>
</tr>
<tr>
<td>Macro+10WLAN</td>
<td>500</td>
<td>1340</td>
<td>2.063</td>
<td>1320</td>
<td>2.063</td>
<td>18.9</td>
</tr>
</tbody>
</table>

For a target of \(3 \text{ bits/sec/Hz/km}^2\) in BH Uniform Traffic Distribution, Table shows Macro 10WLAN is the best HETNET case with around \(19\%\) power saving compared to Macro Only deployment.

### 4.10.2 Area Spectral Efficiency Target 6bits/sec/Hz/km² for BH Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved(m)</th>
<th>Minimum APC distance(m)</th>
<th>Power Consumption at Minimum APC distance(kWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance(kWatt)</th>
<th>% of Power Saving compared to Macro Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>500</td>
<td>1260</td>
<td>1.844</td>
<td>580</td>
<td>4.461</td>
<td>0.0</td>
</tr>
<tr>
<td>Macro+3Pico</td>
<td>500</td>
<td>1360</td>
<td>2.136</td>
<td>900</td>
<td>2.882</td>
<td>35.4</td>
</tr>
<tr>
<td>Macro+5Pico</td>
<td>500</td>
<td>1420</td>
<td>2.309</td>
<td>1040</td>
<td>2.751</td>
<td>38.3</td>
</tr>
<tr>
<td>Macro+10WLAN</td>
<td>500</td>
<td>1340</td>
<td>2.063</td>
<td>900</td>
<td>2.717</td>
<td>39.9</td>
</tr>
</tbody>
</table>

33
For a target of 6 bits/sec/Hz/km\(^2\) in BH Uniform Traffic Distribution, Table shows that **Macro+10WLAN** deployment is the best in terms of energy efficiency with around 40\% power saving compared to Macro Only deployment.

### 4.10.3 Area Spectral Efficiency Target 3bits/sec/Hz/km\(^2\) for BH NON-Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved (m)</th>
<th>Minimum APC distance (m)</th>
<th>Power Consumption at Minimum APC distance (kWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance (kWatt)</th>
<th>% of Power Saving Compare to Macro Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>860</td>
<td>2.387</td>
<td>-</td>
</tr>
<tr>
<td>Macro+3Pico</td>
<td>400</td>
<td>1360</td>
<td>2.136</td>
<td>1100</td>
<td>2.324</td>
<td>2.6</td>
</tr>
<tr>
<td>Macro+5Pico</td>
<td>400</td>
<td>1420</td>
<td>2.309</td>
<td>1240</td>
<td>2.390</td>
<td>-</td>
</tr>
<tr>
<td>Macro+10WLAN</td>
<td>400</td>
<td>1340</td>
<td>2.063</td>
<td>1340</td>
<td>2.063</td>
<td>14</td>
</tr>
</tbody>
</table>

For a target of 3 bits/sec/Hz/km\(^2\) in BH NON-Uniform Traffic Distribution, Table shows that **Macro+10WLAN** deployment is the best in terms of power savings.
### 4.10.4 Area Spectral Efficiency Target 6bits/sec/Hz/km² for BH NON-Uniform Traffic Distribution

<table>
<thead>
<tr>
<th>Deployment Type</th>
<th>ISD where target ASE achieved (m)</th>
<th>Minimum APC distance (m)</th>
<th>Power Consumption at Minimum APC distance (kWatt)</th>
<th>Optimum Distance (m)</th>
<th>Area Power Consumption at Optimum distance (kWatt)</th>
<th>% of Power Saving Compare to Macro Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro Only</td>
<td>400</td>
<td>1260</td>
<td>1.844</td>
<td>620</td>
<td>3.960</td>
<td>-</td>
</tr>
<tr>
<td>Macro+3Pico</td>
<td>400</td>
<td>1360</td>
<td>2.136</td>
<td>760</td>
<td>3.704</td>
<td>6.5</td>
</tr>
<tr>
<td>Macro+5Pico</td>
<td>400</td>
<td>1420</td>
<td>2.309</td>
<td>820</td>
<td>3.788</td>
<td>4.5</td>
</tr>
<tr>
<td>Macro+10WLAN</td>
<td>400</td>
<td>1340</td>
<td>2.063</td>
<td>920</td>
<td>2.643</td>
<td>33.3</td>
</tr>
</tbody>
</table>

For a target of 6 bits/sec/Hz/km² in BH NON-Uniform Traffic Distribution, Table shows that **Macro +10WLAN** deployment is the best in terms of energy efficiency with around **33%** power saving compared to Macro Only deployment.
4.11 Area Power Consumption (minimum) VS Area Throughput (Heterogeneous Uniform Traffic)

Area Throughput is calculated by multiplying ASE with 5MHz (3G) bandwidth. For calculation of minimum APC, the same procedures have been used as defined in section 4.10 i.e. optimizing the ISD in terms of APC for different Area Throughput requirements.

![Minimal Area Power Consumption vs Area Throughput Targets](image)

**Fig 4.11 APC (min) vs Area Throughput (Uniform Traffic)**

The above figure shows APC (minimum) vs Area Throughput for uniform traffic distribution scenario (heterogeneous). From the figure it is clear that for Throughput targets of less than 10Mbps/km², Macro Only is better. But for all the targets greater then 10Mbps/km², HETNET’s show better Energy Efficiency than Macro Only.
4.12 Area Power Consumption (minimum) VS Area Throughput (Heterogeneous NON-Uniform Traffic)

The above figure shows APC (minimum) vs Area Throughput for NON-Uniform traffic distribution scenario (heterogeneous). In NON-Uniform Traffic, Macro+10WLAN (HETNET) case shows the best performance in terms of power savings.
4.13 Verification Process:
Verifications for the simulations are used to establish that a system meets technical standards. In this Thesis, a verification process was performed in Electrum Building Kista, Stockholm in BH of the day. The Electrum building was selected because of its typical Indoor office environment and close proximity with the Thesis location. Electrum Building snapshots are given below:

Fig 4.13: Electrum Main lobby [31]  
Fig 4.14: Wireless@KTH Department 4th Floor Electrum [31]

For the verification, it was decided to calculate ASE only for operator Telia on the technology 3G. For the calculation of APC, there were numerous parameters that were unknown and mobile operators were reluctant to provide these parameters.

4.13.1 Verification Procedure
Verification was performed using TEMS software provided to Wireless Department at KTH by ASCOM. The TEMS tool kit (Sony Ericsson Z750i) was interfaced to Laptop as shown in figure 3.1. TEMS software was used to calculate the SIR values downlink at different points in Electrum. The downlink SIR was measured at 20 different points. The points were selected randomly throughout the Electrum with some values taken inside Wireless@KTH office. It is recognized that values are taken in such a way that, only that time interval of measured values were saved on log file when there was a call in progress between TEMS phone and friends phone or when I used bredbandskollen.se to check the highest bit rate in downlink. In this way I was somewhat able to construct the scenario in which there was some traffic (active user). The log files generated by TEMS were converted in to text format and then data was imported in to excel sheet in order to attain the mean of the received samples of SIR. Since TEMS measures the value
of SIR in dB, the dB values were first converted to ratio and then used formula 2.8 to get spectral efficiency. After that, the mean of the all values of Spectral efficiencies were calculated to attain a single value of average SE. The detailed procedure of how to convert log file to excel file is explained in Appendix D.

4.13.2 ISD Approximation
To get to know the ISD of Telia BS(3G) around Kista (Stockholm) Area, my Thesis advisor Mats Nilson asked his friend Jesper Simons who has a lot of experience in working in Swedish Regulator PTS and his reply was as follow:

"In central urban areas (Stockholm), a site to site distance to be as low as about 200-300 meters, in malls, sports arenas and other heavily used sites, etc., it is even closer, but they often count as exempt special sites. Moreover, a larger number of parameters taken into account, one must take into account given population patterns (eg, SCB's population boxes), market share, busy hour, cut Erlang in the network and traffic patterns, etc. Kista is a bit special when you have a shopping mall in the middle, a trade show, and an incredible number of offices. I do not have an exact figure for the entire chest, but my estimate is that for example 3G has an outer grid, which is about 400 meters (site to site)."

The ISD for measured value was assumed to be 400m.

4.13.3 Analysis of the Measured Value:
The measured value in Electrum Building (Kista) comes out to be around 6 bits/sec/Hz/km² while the simulated value at ISD 400m for Uniform and Non-Uniform Traffic Distribution is approximately 12 bits/sec/Hz/km².

There could be a number of reasons for this discrepancy with some of them given below:

1) The WCDMA hardware/software does not perform according to the Shannon limit, there are implementation margins both in the system standard and the actual TEMS units used.
2) TEMS Investigation absolute measurement accuracy (estimated to be 1 or 2 dB maximum)
3) The ISD value of 400m that was used for verification is not accurate.
4) The wall attenuation used in the simulations is around 14db but in the actual scenario it might be much higher than 14db.
5) The BS antennas are considered in the centre of hexagon but in the real deployment, antennas and cell shape are adjusted according to the Area population and traffic distribution.
6) The antenna gain, transmitted power and height of BS that were used in simulations can be different with the actual values.
7) The number of active users in the area might be different from simulations.

The measured value in this Thesis is added to give just an idea that how to perform verification for above mentioned simulations. Extensive measurements at different Indoor locations are required to get a better comparison.
4.14 Data Availability

Data availability for 1 User/Month (Homogenous)

4.14.1 Macro Only
Macro Only data availability for 1 User/Month is calculated as follow:

The data availability for BH at optimum ISD was calculated and then repeated the same procedure for Non-BH. After that, the average of the two available data/user/month.

4.14.1.1 Busy Hour:
Bandwidth assumed = B =5MHz, ASE=3bits/sec/Hz/km², ISD=D=650m

Number of Active Users = 150 in 3 Macro Cells (Total Area) = 50 Users/Cell

Assuming 1 User Connected to BS for 8 Hours / Day

R= D/sqrt (3) => R=375m

Area of a Cell = (3*sqrt(3)/2)*(R/1000)^2 = 0.366 km²

Average Throughput = B*Area*ASE = 5.4884 Mbps

Average Data Available in Giga bytes User/ Month = (Average Throughput*60*60*30*8) / 50*8

= 5.4884 *60*60*30*8 /50*8

= 11.855 GB / User / Month

4.14.1.2 NON-Busy Hour:
Bandwidth assumed = B =5MHz, ASE=3bits/sec/Hz/km², ISD=D=650m

Number of Active Users = 30 in 3 Macro Cells = 10 Users/Cell

Average Data Available in Giga bytes User/ Month = 59.28 GB / User / Month

Average Data Available to User/ Month (MACRO) = 11.855 + 59.28 /2

= 35.57 GB /User /Month (4.1)

4.14.2 Micro Only
Same procedure as followed for Macro Only

4.14.2.1 Busy Hour:
Bandwidth assumed = B =5MHz, ASE= 6 bits/sec/Hz/km², ISD=D=380m
Number of Active Users = 150 in 12 Micro Cells = 13 Users/Cell
Average Data Available in Giga bytes User/ Month = (Average Throughput*60*60*30*8) / 13*8
= 30.45 GB / User / Month

4.14.2.2  NON-Busy Hour:
Bandwidth assumed= B =5MHz, ASE=6 bits/sec/Hz/km², ISD=D=380m
Number of Active Users = 30 in 12 Micro Cells = 3 Users/Cell
Average Data Available in Giga bytes User/ Month =  131 GB / User / Month

Average Data (BH+NBH) Available to User/ Month (MICRO) = (131+30.45) / 2
= 81.1 GB /User /Month  (4.2)  

4.15 Data availability for 1 User/Month (Heterogeneous)

4.15.1 Macro + 3Pico
Bandwidth assumed= B =5MHz, ASE=6 bits/sec/Hz/km², ISD=D=760m, NON-Uniform Traffic Distribution, Busy Hour.

Average Data Available (Non-Uniform) in Giga bytes User/ Month = 93 GB / User / Month
= 93 GB /User /Month  (4.3)

4.15.2 Macro + 5Pico
Bandwidth assumed= B =5MHz, ASE=6 bits/sec/Hz/km², ISD=D=820m, NON-Uniform Traffic Distribution, Busy Hour.

*Assuming half of Pico Cells have No Cellular Traffic.

Number of Active Users = 200 in 3 Macro and 8 Pico Cells = 18 Users/Cell
Average Data Available for Macro+5Pico = 102 GB / User / Month  (4.4)

4.15.3 Macro + 10 WLAN
Bandwidth assumed= B =5MHz, ASE=6 bits/sec/Hz/km², ISD=D=920m, NON-Uniform Traffic Distribution, Busy Hour.

*Assuming half of WLAN’s are unused.

Number of Active Users = 200 in total 3 Macro and 15WLAN = 11 Users/Cell
Average Data Available in Giga bytes User/ Month = 167 GB / User / Month  (4.5)
5 Conclusions & Future Work:

5.1 Simulation Analysis & Recommendations (Homogeneous)

Simulations gave a clear picture for best Indoor coverage and capacity in terms of energy efficiency in homogeneous deployments. The results show that if a larger ASE is required indoors, Micro BS only deployment is a better energy efficient solution for both Uniform and Non-Uniform traffic distribution. This is because higher number of micro BS will result in less distance between Mobile Station and BS, which will enhance propagation conditions and ultimately ASE. Also, due to smaller cell sizes of Micro networks, mobiles located near the cell borders will receive more power which will balance out the interfering power because of non-linear propagation conditions. By lowering the ASE demand, the Micro BS does not remain power efficient compared to Macro BS only. This result is logical as lower ASE can be achieved with Macro BS which are deployed outside and comparatively less in number to Micro BS. Thus, there is a tradeoff between ASE and APC.

The results confirm the literature study [32] that if a wireless network architect wants higher mean ASE in a system, then pure micro deployment is a better option.

5.2 Simulation Analysis & Recommendations (Heterogeneous)

Simulation in heterogeneous deployments gave a clear picture for best Indoor coverage and capacity in terms of energy efficiency. For Uniform Traffic Distribution cases, we can see that Macro+10WLAN is the best energy efficient solution for both ASE targets. Also as the ASE target for Uniform Traffic Distribution increases, the HETNET deployments became more energy efficient compared to Macro Only deployment. In case of Non-Uniform Traffic Distribution, the most energy efficient deployment is also Macro+10WLAN. This might be because high number of WLAN and much less Power Consumption of WLAN compared to Pico BS.

The results above verify a number of literature studies that HETNET’s are much more energy efficient solutions and increase the system average data rate compared to high power traditional Macro’s Only. The simulation results above are highly dependent on Linear Power models, Propagation Models, position of HotSpots in simulation, number of active users and Inter Site Distances. Also, taking average ASE as primary metric, the results above will vary if users with different categories (premium or Non-premium) are introduced.

In the end, approximate data available / User / Month were calculated. According to the calculations in homogeneous case, Micro can provide almost twice the data /user/month than Macro. In the heterogeneous case, Macro+10WLAN provide highest data/User/Month compared to other HETNET cases.
5.3 Future Work:
The results in the Thesis gave idea about how energy efficiency improvements can be achieved in different scenarios for Indoor Traffic. In future, traffic distribution of the users can be modeled more accurately to simulate real scenarios. In this thesis average ASE is considered but a more realistic ASE, depending upon the user demand for a specific area could be used for future work. Measurements performed in this thesis are there to give an idea about verification process. More measurements can be performed in different Indoor scenarios and at different ISD’s to get better comparisons. Cost Analysis can also be added to get understanding of which deployment (Homogeneous or Heterogeneous) is best, CAPEX and OPEX wise, for certain QoS requirements.
References


[22] “IST-4-027756 WINNER II D1.1.2 V1.2 WINNER II Channel Models”, Available at: http://www.ero.dk/93F2FC5C-0C4B-4E44-8931-00A5B05A331B?frames=no&, Visited 15th October, 2011.


### Appendix A

**WCDMA SPECIFICATIONS:**

**Table A.1 [33]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band UL</td>
<td>1920MHz – 1980MHz</td>
</tr>
<tr>
<td>Frequency Band DL</td>
<td>2110MHz-2170MHz</td>
</tr>
<tr>
<td>Frequency Reuse</td>
<td>1</td>
</tr>
<tr>
<td>Receiver Sensitivity Mobile</td>
<td>-120dBm at BER 10^{-3}</td>
</tr>
<tr>
<td>Chip Rate</td>
<td>3.84Mcps</td>
</tr>
<tr>
<td>Maximum User data rate</td>
<td>Upto-10Mbps</td>
</tr>
<tr>
<td>Frame length</td>
<td>10ms</td>
</tr>
<tr>
<td>Number of slots</td>
<td>15</td>
</tr>
<tr>
<td>Handovers</td>
<td>Soft, Softer</td>
</tr>
<tr>
<td>Receiver</td>
<td>Rake</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK HSPA+</td>
</tr>
</tbody>
</table>
Appendix B

Table B.1 [7][8][3][25]

<table>
<thead>
<tr>
<th>BS type</th>
<th>A</th>
<th>B</th>
<th>Ptx(watt)/(dBm)</th>
<th>At this ISD(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>22.6</td>
<td>412.4</td>
<td>4.7/37</td>
<td>1000</td>
</tr>
<tr>
<td>Micro</td>
<td>7.84</td>
<td>71.5</td>
<td>3/35</td>
<td>347</td>
</tr>
<tr>
<td>Pico</td>
<td>5.14</td>
<td>58.2</td>
<td>1.9/33</td>
<td>200</td>
</tr>
<tr>
<td>WLAN</td>
<td>3.2</td>
<td>7.2</td>
<td>0.15/21</td>
<td>50</td>
</tr>
</tbody>
</table>

**Note:** The Ptx (watt) value will increase systematically as the Range (m) will increase.

Table B.2 [7][8][3][34]

<table>
<thead>
<tr>
<th>BS type</th>
<th>Antenna Gain (dBi)</th>
<th>Max. Downlink Transmitted Power(dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>15</td>
<td>46</td>
</tr>
<tr>
<td>Micro</td>
<td>6</td>
<td>39</td>
</tr>
<tr>
<td>Pico</td>
<td>3</td>
<td>33</td>
</tr>
<tr>
<td>WLAN</td>
<td>0</td>
<td>21</td>
</tr>
</tbody>
</table>

Downlink Transmitted Power is the power transmitted from Base Station to Mobile Station for a carrier. Antenna gains are standard gains found in literature for different types of BS [13].
## Appendix C

### Table C.1 [34][7][8][35]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Macro</th>
<th>Micro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>5-20Mhz</td>
<td>5-20Mhz</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.1Ghz</td>
<td>2.1Ghz</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>15dBi</td>
<td>6dBi</td>
</tr>
<tr>
<td>Sectors</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Antenna Pattern</td>
<td>Omni</td>
<td>Omni</td>
</tr>
<tr>
<td>Cell Radius</td>
<td>Variable</td>
<td>Variable</td>
</tr>
<tr>
<td>Noise Figure</td>
<td>4dB</td>
<td>4dB</td>
</tr>
<tr>
<td>Receiver Sensitivity</td>
<td>-120dBm</td>
<td>-120dBm</td>
</tr>
<tr>
<td>Base Station Height</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Average Building Height</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Street Width</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Number of Walls Indoor between UE and MS (X=5n_w-1)</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Fading</td>
<td>8dB</td>
<td>4dB</td>
</tr>
<tr>
<td>Service Area</td>
<td>Sub-Urban /Indoor</td>
<td>Indoor</td>
</tr>
<tr>
<td>Penetration Loss from Outside (Wall loss)</td>
<td>15-20dB</td>
<td>0dB</td>
</tr>
<tr>
<td>Daily Profile</td>
<td>Office</td>
<td>Office</td>
</tr>
<tr>
<td>UE NF</td>
<td>7dB</td>
<td>7dB</td>
</tr>
<tr>
<td>UE Path Loss from MACRO</td>
<td>PL_{NLOS} = 39.08*Log_{10} (d) + 12.8489 + Wall loss</td>
<td></td>
</tr>
<tr>
<td>UE Path Loss from MICRO</td>
<td>PL_{LOS} =36.8*Log_{10} (d) + 36.265 + X</td>
<td></td>
</tr>
</tbody>
</table>
Appendix D

Scan & Export Log files from TEMS

First of all we have to set up the scanning procedure in TEMS investigation Software. The TEMS will scan the entire data parameters of 3G connection including Channel number, RSSI, SIR, Target SIR, Throughput etc. The scanning can be performed for any time interval. I have performed scanning for the time interval mentioned above. Once the scanning is over, you can press stop scan and save the log file. After that you can disconnect the device which will enable the open log file menus option. Select the log file on which you have done the recording. You can then choose the export log file option present in the log file menu [31].

![Fig D1: Exporting log file from TEMS](image)

This sort of menu will pop up. Choose the text file option and then select the setup option following window will open up.
Select following parameter for WCDMA and add it in the selected IE as shown in above figure. The parameter is “**SIR (db)**”. Afterwards select the edit button and choose the external equipment that is connected to TEMS investigation software and in the argument drop list and then press ok.

After doing the above mentioned steps, the window looks like this. Then press the start scanning button and run the scan on the selected file which you have given. Once the scanning is
completed, call the file in the Excel Spreadsheet. Press the data menu and then press the option import data. You have to select some of the options in that menu and then the entire text file would be transferred on to the excel sheet. The data exported will look something like this:

![Excel Spreadsheet](image)

**Fig D4: View of data imported from TEMS Investigation to Microsoft Excel sheet**

Here I have calculated the average SIR and Spectral Efficiency at some measurement point.
APPENDIX E

RUNE SIMULATOR CONFIGURATION
The RUNE Simulator consists of numerous functions that are used to simulate different cellular scenarios. For this Thesis, main function runefc (WCDMA simulations) which is part of RUNE is used. In runefc, there are many secondary functions that are present. Some of these secondary functions mentioned below have been changed to fulfill the requirements of this Thesis.

Pathgain
In this function path loss models have been added. For Macro, Outdoor to Indoor Model (2.2) has been added while for Micro / Pico/ WLAN, Indoor Model (2.6) has been added.

Setparc
In this function, different parameters have been set to values according to the Thesis case. These parameters include distance attenuation coefficient, standard deviation, initial downlink power set for each link, sectors per site and chiprate.

Handoffc
In this function, handoff has been optimized for different site types. The values of downlink transmitted power of HETNET sites have been changed.

Crecells
In this function cells are created according to inputs, another function is added for creation of HETNET cells as shown in figure 4.7.

Note: Some of the functions added in RUNE for calculation of Area Power Consumption and Area Spectral Efficiency.

Power (Macro Only)
This function calculates the APC for the Area covered by Macro Only BS.

Power (Micro Only)
This function calculates the APC for the Area covered by Micro Only BS.

Power (HETNET)
This function calculates the APC for HETNET.

Average ASE Calculation
This function calculates the Average ASE at different ISD for homogeneous and heterogeneous cases. Runefc main function is called in this function at every ISD value.

Hotspots Location and Traffic Distribution
These functions calculate the hotspots positions and distribute traffic for Non-Uniform case.
**RUNE Simulation Code:**

**PathGain (Code):**

```matlab
function g = pathgain(xym, xyb, fib, asps, rhombvec, gainconst, alpha, ...
    sigma, raa, lognmap, mapvec, sitetype)

if isempty(xym)
    g = zeros(0,size(xyb,2)); % Set to an empty matrix.
    return
end

% Wrap around in 7 positions.
    r = 0;
if sum(abs(rhombvec))>0 % no rhombvec, no wrap around
    r = flatten(crecluster(1,2,rhombvec(1)),3); % wrap 7 possible positions
end
    wad = mplus(xym, -xyb, r);% Distance calculation.

if (strcmp('macro',sitetype))
    %MACRO INDOOR MODEL
    wallloss=14*ones(size(xym,1),size(xyb,2));
    wallloss2=14*ones(xym1,size(xyb,2));
    temp=-mprod(39.08,log10(max(10,abs(wad))));%AT CELL EDGE
    wallloss1=zeros(size(xym,1),size(xyb,2));
    wallloss1(1:xym1,:)=wallloss1(1:xym1,:)+wallloss2;
    temp2=-(wallloss+12.8489*ones(size(xym,1),size(xyb,2))));%100% users indoors
    gatt=mplus(temp,temp2);
end
%%%%%%%%%%%%%%%%%%%%%%%%MICRO MODEL////////////////PROFILE
if (strcmp('pico',sitetype))||(strcmp('wlan',sitetype))||(strcmp('micro',sitetype))
    n=2;
    Wall_loss=5*(n-1);
    attenuation3=36.265*ones(size(xym,1),size(xyb,2));
    attenuation4=-(attenuation3+Wall_loss*ones(size(xym,1),size(xyb,2)));
    temp3=-mprod(36.8,log10(max(10,abs(wad))));
    gatt=mplus(temp3,attenuation4); %AT CELL EDGE
end
% Angle attenuation between direction to mobiles and cell main direction added.
    gant = antennagain(angle(mdiv(fib,wad)),1/asps,sitetype);
% Select the position with highest gain of all wrap positions
    g = max(gant+gatt,[],3);
    clear gatt; % These may be big.
    clear gant;
    clear wad;

% Lognormal fading with base station correlation.
if sigma ~=0
    % Create a random base offset.
    oseed = setseed(1);
    maxdist = max(flatten(abs(mplus(xyb,-xyb.')))); % max distance
    xyboffs = irand(size(xyb))*maxdist*10; % scramble base pos
```
setseed(oseed);
% Calculate the log normal gain
\[
g = g + \sigma \cdot \text{mplus}(\ldots
\sqrt{1 - raa} \cdot \text{uselognmap}(\text{mplus}(-xym, xyoffs), \text{lognmap}, \text{mapvec}), \ldots
\sqrt{raa} \cdot \text{uselognmap}(xym, \text{lognmap}, \text{mapvec}) \ldots)
\]
end

**Power (Macro Only) Code:**

```matlab
function [dist_pc, Pc] = power_dist()

km = 1;
lm = 1;
sps = 1;
kN = 0;
ln = 1;
sites = km^2 + lm^2 + km*lm;
P = [];
dis = [];
am = 22.6;
bm = 412.4;
nmacro = 0;

for m = 1:length(nmacro)
    num = nmacro(m);
    for D = 400:20:1600
        dis = [dis, D];
        R = D/sqrt(3);  \% calculation for cell radius
        Area = (3*sqrt(3)/2)* (R/1000)^2;
        Wall_Loss = 14;
        PathLoss = 12.8489 + 39.08*(log10(R*0.95)) + Wall_Loss;
        gain = 15;
        NF = 0;
        MS_GAIN = -1;
        pmin = -110;
        ptx_db = NF + PathLoss - gain + pmin - MS_GAIN;
        temp = ptx_db/10;
        ptx = 10^temp;
        Pm = am * ptx + bm;
        Pt = (sites * Pm)/Area;
        Pt = Pt/1000;
        P = [P, Pt];
    end
end

dist_pc = dis;
```

Average ASE Calculation (Code):

```matlab
clear All;
par = setparc;
par.raa = 0.5;
par.usefastf = 0;
par.offtraf = load;
par.sps = 1;
par.km=1;
par.lm=1;
par.seed=randi(1000,1)+200;
sites = par.km^2 + par.lm^2 + par.km*par.lm;
Pmin = -120;
dist = [];
data_rate = [];

par.offtraf = load/sites;

for D=400:20:1600;  %Macro Only
    R = D/sqrt(3);  %calculation for cell radius
    par.cellradius = R;
    Area = (3*sqrt(3)/2)*((R/1000)^2);
    [res, par, sta, sys] = runefc(par);
    temp = max(sta.sirdmb,[],2);
    data_rate_per_cell = zeros(1,length(sys.xyb));  %bits/sec/Hz/km^2~
    for i=1:length(sys.xyb)  %%%number of BS
        for j=1:length(sta.xym)  %%%number of users
            if(sta.sirdmb(j,i) == temp(j,1))
                data_rate_per_cell(i) = data_rate_per_cell(i) + (1)*log2(1 + db2lin(sta.sirdmb(j,i)));  %%%IMP.
            end
        end
    end
    total_data_rate = sum(data_rate_per_cell);
    avg_data_rate = (total_data_rate/(Area*sites));
    dist = [dist, D];
data_rate = [data_rate, avg_data_rate];
end
end
end
```