Sudan University of Science and Technology
Faculty of Engineering
Department of Electronic Engineering

Spectrum Requirements for Advanced International Mobile Telecommunications: Sudan Case Study

متطلبات الطيف الترددي لأنظمة الاتصالات الدولية المتنقلة المتقدمة :
دراسة الحالة السودانية

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قال تعالى : {وَلَا تَقُولَنَّ لِشَيْءٍ إِنِّي فَاعِلٌ ذَٰلِكَ غَدًا (23) إِلَّا أَنْ يَشَاءَ اللَّهُ ۚ وَاذْكُرْ رَبَّكَ إِذَا نَسِيتَ وَقُلْ عَسَىٰ أَنْ يَهْدِيَنِ رَبِّي لِأَقْرَبَ مِنْ هَٰذَا رَشَدًا (24)}

To my beloved family,

Who always encouraging me and uplifting my spirit by supporting me all the way along...

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ABSTRACT

To deploy the IMT-Advanced technologies in Sudan (Republic of) we must know how much radio spectrum resources that we need, and by determining the required spectrum for the Sudan we could help the regulatory body taking their decisions and actions.

In this thesis, we determined Sudan IMT-Advanced technology requirements, and studied the market behavior and forecast the needs in the future, and then customized a new model with different scenarios to estimate the required spectrum for Sudan to be able to use the IMT-Advanced till 2025. These scenarios were modeled according to the number of operators that may use these technologies with a precaution to any new entrants in the future.

To calculate the required spectrum the ITU-R SPECtrum requirement calcULATOR "SPECULATOR" model was used, and it had been customized to meet the Sudan market situations and forecasts.

المستخلص

لنشر تكنولوجيات الاتصالات المتنقلة الدولية المتقدمة في السودان يجب معرف كمية موارد الطيف الترددي التي نحتاجها، وبتحديد كمية الطيف الترددي المطلوبة للسودان يمكن مساعدة الهيئة التنظيمية في اتخاذ قراراتهم و اجراءاتهم.

في هذه الأطروحة تم تحديد المتطلبات التكنولوجية لأنظمة الاتصالات الدولية المتنقلة المتقدمة في السودان، ودراسة سلوك السوق ، والتنبؤ باحتياجات المستقبل، ومن ثم تخصيص نموذج جديد بعدة سيناريوهات مختلفة لتقدير الطيف الترددي المطلوب للسودان ليكون قادراً على استخدام أنظمة الاتصالات الدولية المتنقلة المتقدمة حتى عام 2025. و تم نمذجة هذه السيناريوهات وفقاً لعدد الشركات التي قد تستخدم هذه التقنيات ، مع وضع الاحتياطات اللازمة لأي مشاركين جدد في المستقبل.

لحساب كمية الطيف المطلوبة تم استخدام انموذج الاتحاد الدولي للاتصالات الراديوية لحساب كمية الطيف الترددي المطلوبة "SPECULATOR“، و تم تخصيص هذا الانموذج لتلبية أوضاع السوق والتوقعات في السودان.

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List of Abbreviations

2G   2nd Generation

3G   3rd Generation

3GPP   3rd Generation Partnership Project

4G   4th Generation

BER   Bit Error Rate

DL   Downlink

E-UTRA   Evolved UMTS Terrestrial Radio Access

FDD   Frequency Division Duplex

FP5   Framework Programme 5

GSA   Global mobile Suppliers Association

HDTV   High-definition television

IMT-2000   International Mobile Telecommunications-2000

IMT-Advanced   International Mobile Telecommunications-Advanced

IST   Information Society Technologies

ITU   International Telecommunication Union

LTE   Long Term Evolution

MIND   Mobile IP-based Network Developments project

MMS   Multimedia Messaging Service

MNOs   Mobile Network Operators

MVNOs   Mobile Virtual Network Operators

QoS   Quality of Service

RATGs   Radio Access Technology Groups

RATs   Radio Access Techniques

REs   Radio Environments

RLANs   Radio Local Area Networks

RR   Radio Regulations

SC   Service Category

SE   Service Environments

SG   Study Group

SPECULATOR   SPECtrum requirement calcULATOR

TDD   Time Division Duplex

UL   Uplink

VoIP   Voice over Internet Protocol

WINNER   Wireless World Initiative New Radio

WLAN   Wireless Local Area Network

WP5D	Working Party 5D
WP8F	Working Party 8F
WRC-07	World Radiocommunication Conference 2007
WRC-15	World Radiocommunication Conference 2015

CHAPTER ONE

Introduction

1.1 Background

International Mobile Telecommunications-Advanced (IMT-Advanced) systems are mobile systems that include new capabilities of IMT that go beyond IMT-2000, which is widely deployed since 2000 and referred to as 3G mobile technologies. ITU has now specified the standards for IMT-Advanced, the next-generation global wireless broadband communications that provide access to a wide range of packet-based telecommunication services supported by mobile and fixed networks.

An IMT-Advanced system is expected to provide a comprehensive and secure all-IP based mobile broadband solution to laptop computer wireless modems, smartphones, and other mobile devices. Facilities such as ultra-broadband Internet access, IP telephony, gaming services, and streamed multimedia may be provided to users.

IMT-Advanced systems are currently being specified by the ITU-R. Until October 2007, IMT issues were under the responsibility of the Working Party 8F (WP8F) of ITU-R. They will support a rich variety of mobile services and applications with a peak user data rate of 100 Mbit/s for highly mobile terminals and up to 1 Gbit/s for slowly moving terminals in metropolitan areas.

IMT-Advanced systems support low to high mobility applications and a wide range of data rates in accordance with user and service demands in multiple user environments. IMT-Advanced also has capabilities for high quality multimedia applications within a wide range of services and platforms, providing a significant improvement in performance and quality of service.

IMT-Advanced intended to accommodate the quality of service (QoS) and rate requirements set by further development of applications like mobile broadband access, Multimedia Messaging Service (MMS), video chat, mobile TV, but also new services like High-definition television (HDTV). 4G may allow roaming with wireless local area networks, and may interact with digital

video broadcasting systems. It was meant to go beyond the International Mobile Telecommunications-2000 requirements, which specify mobile phones systems marketed as 3G.

Specific requirements of the IMT-Advanced report included:

1. A nominal data rate of 100 Mbit/s while the client physically moves at high speeds relative to the station, and 1 Gbit/s while client and station are in relatively fixed positions.
2. Scalable channel bandwidth 5–20 MHz, optionally up to 40 MHz.
3. Peak link spectral efficiency of 15 bit/s/Hz in the downlink, and 6.75 bit/s/Hz in the uplink (meaning that 1 Gbit/s in the downlink should be possible over less than 67 MHz bandwidth).
4. System spectral efficiency of up to 3 bit/s/Hz/cell in the downlink and 2.25 bit/s/Hz/cell for indoor usage.

1.2 Problem Statement

It is well-known that the radio spectrum is a valuable and limited natural resource as it is generally available within a range of between 3 kHz and 3000 GHz for communications purposes.

Now in the Sudan there are 3 mobile services operators and 1 fix services operator, and it may increase anytime, So they may need to upgrade to new technologies to get the benefits of it, de facto that the Sudan is one of the most developed and precursors countries in the African continent in the telecommunication field.

To deploy the IMT-Advanced technologies in Sudan we need to know how much radio spectrum resources that we need, and by determining the required spectrum for the Sudan we could help the regulatory body taking their decisions according to their needs.

The purpose of this research is to estimate the required spectrum for the Sudan to be able to use the IMT-Advanced technologies with different scenarios (estimate the number of operators that's may be ready to use this technology).

1.3 Motivation

The spectrum requirements estimation for IMT-advanced is a very important issue for both of the operators and the regulatory body of the country. But in fact it's more important for the regulatory body than the operator because it's responsible for Laying down the plans, policies, regulations, allocation and licensing for the provision of the telecommunication services.

Nowadays there is a huge dispute in the telecommunication field all over the world regarding the IMT-advanced spectrum allocation, and there are a lot of candidate spectrum bands, and each of these candidate bands has its characteristics.

So, by determining the required spectrum for the Sudan we could help the regulatory body taking the right decision according to their needs, and build a solid floor for their decisions that's may help them in the Global forums and conferences, such as the World Radiocommunication Conference 15 (WRC-15).

1.4 Hypotheses

In the spectrum requirements calculation model we assume that the market study will be the same as in the Report ITU-R M.2078 "Estimated spectrum bandwidth requirements for the future development of IMT-2000 and IMT-Advanced", and Report ITU-R M.2290 "Future spectrum requirements estimate for terrestrial IMT", with a little crosscheck to make sure that it could be used to estimate the required spectrum.

Also the number of population, and the number of these technology users will be estimated based on the given data from a competent authorities.

1.5 Aim and Objectives

The aim of this research is to estimate the required spectrum for the Sudan to be able to use the IMT-Advanced technologies with different scenarios (estimate the number of operators that's may be ready to use this technology during this period), Which could help the regulatory body taking the right decisions according this study, and build a solid floor for it, and this can be done:

1. Gathering sufficient data from the competent authorities regarding this issue, such as user density (for couple years ago and forecast it for the future), also the population coverage

percentage for couple years to the different service environments, and the distribution of Radio environments that are supported these different service environments.

2. Analyzing the data and get conclusion.
3. Customize reference model for the Sudan spectrum requirements.
4. Estimating the spectrum efficiency for the contributed model.
5. Apply the data to the contributed model to check if good results were achieved.

1.6 Thesis Outline

This thesis is organized as follows:

Chapter Two will give more information about IMT-Advanced technologies, deployment implications, and IMT-Advanced spectrum aspects.

Chapter Three - chapter will contains more details about the SPECULATOR model, how to work, how to calculate required spectrum and give the final results.

Chapter Four - will contain the output results from the model under study, and the assumptions that are made to get these results.

Chapter Five - is the last chapter which contains a final discussion about the results of this model will be made regarding the estimated outputs, and how to get useful from these output results in the future.

CHAPTER 2

IMT-Advanced Systems

2.1 Introduction

International Mobile Telecommunications-Advanced (IMT-Advanced) systems are mobile systems that go beyond those of legacy IMT-2000 systems which are used to refer to the third generation mobile systems, and it almost used today by all its developments and enhancements. IMT-Advanced systems include new capabilities of IMT beyond IMT-2000, such as providing an access to a wide range of telecommunication services, which are increasingly packet-based, and also support low to high mobility applications and a wide range of data rates in accordance with user and service demands in multiple user environments [1].

An IMT-Advanced system is expected to provide a comprehensive and secure all-IP based mobile broadband solution to laptop computer wireless modems, smartphones, and other mobile devices. Facilities such as ultra-broadband Internet access, IP telephony, gaming services, and streamed multimedia may be provided to users.

The capabilities of IMT-2000 systems have been continuously enhanced over the past decade as IMT-2000 technologies are upgraded and deployed. From the radio access perspective, the evolved IMT-2000 systems have been built on the existing systems and further enhanced the radio interface functionalities, and at the same time, new systems have emerged to replace the legacy radio access systems. This evolution has improved the reliability and throughput of the cellular systems and has promoted the development of an increasing number of services and applications. Similarity of services and applications across different IMT technologies and frequency bands is beneficial to users, and a broadly similar user experience leads to a large-scale deployment of products and services. The technologies, applications, and services associated with systems beyond IMT- Advanced could well be radically different from the present, challenging the perceptions of what may be considered viable by today's standards and going beyond what has just been achieved by the IMT-Advanced radio systems [2].

The key features of IMT-Advanced are:

- A high degree of commonality of functionality worldwide while retaining the flexibility to support a wide range of services and applications in a cost efficient manner;

- Compatibility of services within IMT and with fixed networks;

- Capability of interworking with other radio access systems;

- High-quality mobile services;

- User equipment suitable for worldwide use;

- User-friendly applications, services and equipment;

- Worldwide roaming capability;

- Enhanced peak data rates to support advanced services and applications.

2.2 IMT-Advanced Requirements

Specific requirements of the IMT-Advanced report included:

- Based on an all-Internet Protocol (IP) packet switched network.

- Interoperability with existing wireless standards.

- A nominal data rate of 100 Mbit/s while the client physically moves at high speeds relative to the station, and 1 Gbit/s while client and station are in relatively fixed positions.

- Dynamically share and use the network resources to support more simultaneous users per cell.

- Scalable channel bandwidth 5–20 MHz, optionally up to 40 MHz.

- Peak link spectral efficiency of 15 bit/s/Hz in the downlink, and 6.75 bit/s/Hz in the uplink (meaning that 1 Gbit/s in the downlink should be possible over less than 67 MHz bandwidth).

- System spectral efficiency of up to 3 bit/s/Hz/cell in the downlink and 2.25 bit/s/Hz/cell for indoor usage.

- Seamless connectivity and global roaming across multiple networks with smooth handovers.

- Ability to offer high quality of service for multimedia support.

2.3   IMT-Advanced Evolution

This thesis talks about IMT-Advanced technologies, and mainly the LTE technology and its enhancements, because of the main purpose of this thesis is to get its spectrum requirements to deploy it in Sudan as mentioned in chapter one.

Since the LTE technology deployed for the first time in December 2009 in Sweden, the global LTE market has evolved considerably, and now It is now moving to a more mature phase of development with a hundreds of commercial LTE networks now in operation, with expectation of that there will be close to 500 live LTE networks across 128 countries worldwide, and over one billion connections expected by 2017 [4].
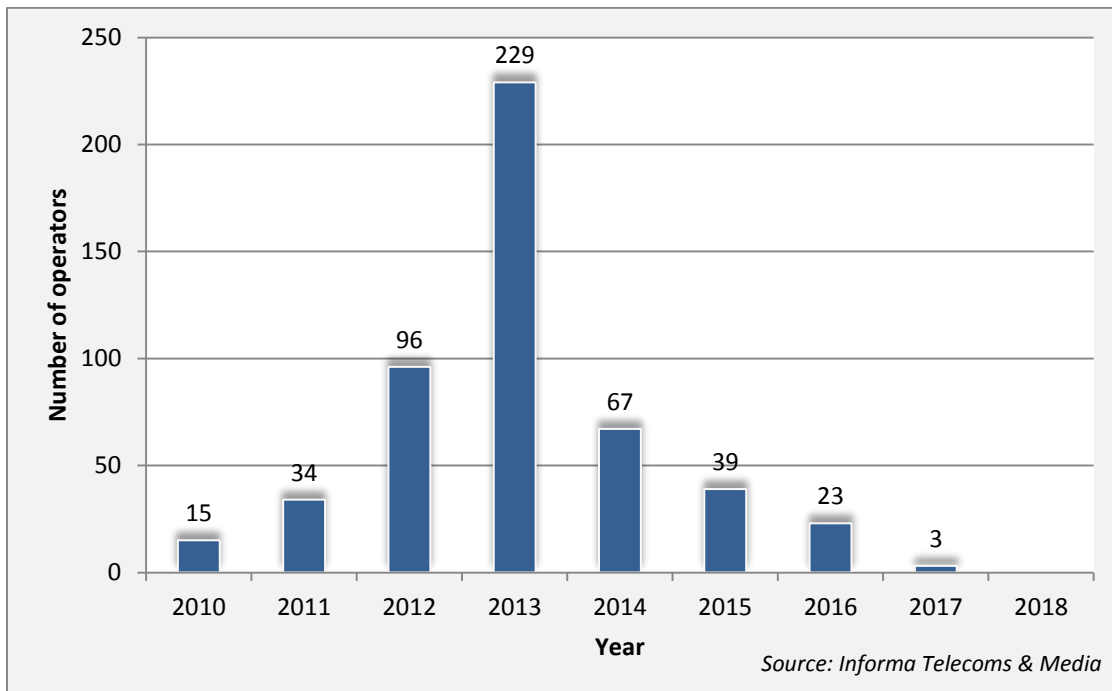
Figure (2.1): Global LTE network launches 2010-2018
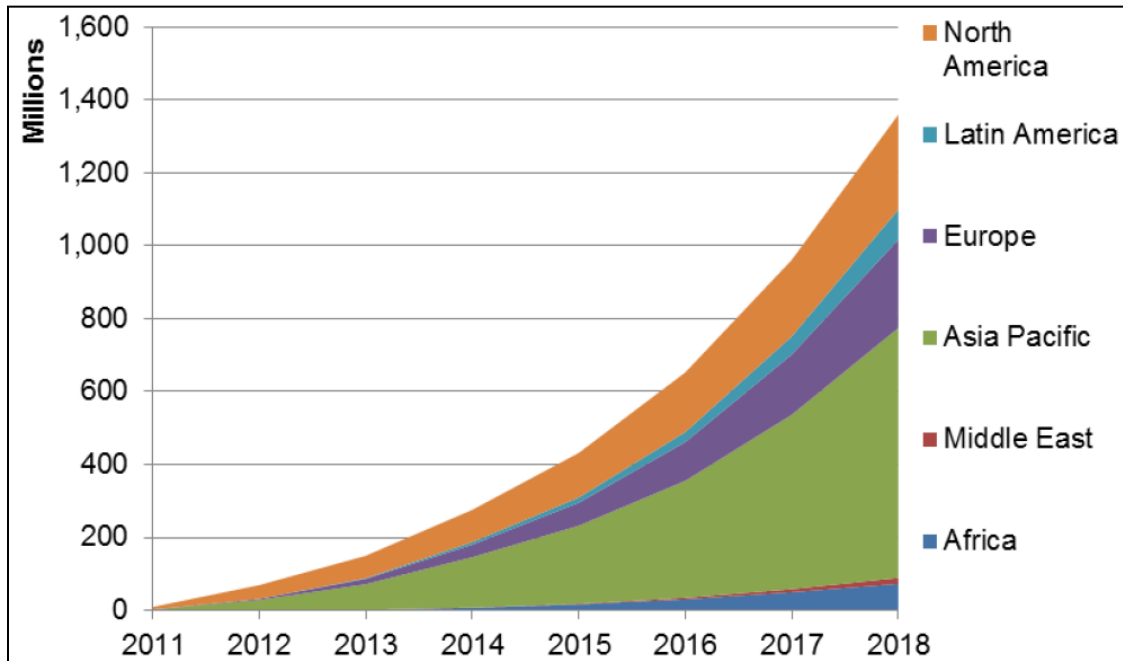
Figure (2.2): Expected LTE subscription growth to 2018

2.4   LTE Deployment Implications

To deploy the LTE technology there are many issues must be considered by the industry and stakeholders, such as the technical implications, business implications, financial implications and regulatory implications.

Regarding the technical implications, it's a well-known that the LTE and 4G technologies can significantly increase mobile network capacity, but achieving those throughputs will be dependent on the amount of radio spectrum assigned, and you may need large amounts of contiguous spectrum bandwidth, which may require existing users to be migrated out of certain bands, and the operators will need to upgrade to network infrastructure to achieve the full capabilities of LTE.

From business point of view the voice calls are considered a high-value revenue stream, since they are measurable with well-established systems for pricing and calculating costs. However, with regard to mobile Internet and data services, the pricing regimes are not as clearly established, and the operators had to protect their revenues since in LTE all traffic is packet-based. Additionally, broadband services consume a considerably larger portion of the network resources in comparison to voice traffic.

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The financial implications represented in the fact that the operators must undertake significant upgrade of existing infrastructure to support 4G, and they are required to acquire additional spectrum in order to realise acceptable speeds and capacities. However, as a national resource, governments place a premium on the sale of spectrum, so prices might be especially high.

Also, as a regulatory implication, it is essential that radio spectrum planning and allocation strategies recognise the future requirements of these networks, and it has to consider many other issues such like infrastructure sharing issues, interconnection issues, pricing and licensing issues.

2.5   IMT-Advanced Spectrum Aspects

There are several spectrum bands have been identified for the IMT and/or IMT-2000 during several World Radiocommunication Conferences (WRC) since WRAC-92, WRC-2000, WRC-07 and WRC-12.

These bands are specified in the Radio Regulations (RR) footnotes as will be clarified in the table below:

Table (2.1): IMT spectrum bands

Spectrum bands	Radio Regulations (RR) footnotes
450-470 MHz	5.286AA
698-960 MHz	5.317A
1710-2025 MHz	5.384A
2110-2200 MHz	5.388
2300-2400	5.384A
2500-2690 MHz	5.384A
3400-3600 MHz	5.430A, 5.432A, 5.432B, 5.433A

De facto that there is no single band has yet emerged as the leading candidate for globally harmonized LTE-frequency adoption, the thing that result in many implications, such as impeding the roaming services for some time, increasing in manufacturers cost since mobile devices already support existing modes, and adding of any more antennas is challenging in terms

of industrial design, and if there is no harmonization in the bands that will lead to increase the prices of the handsets.

According to 3GPP report (3GPP TS 36.101 V12.2.0 (2013-12)) the E-UTRA is designed to operate in the operating bands defined in the table below:

Table (2.2): E-UTRA operating bands as specified by 3GPP

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit		Downlink (DL) operating band BS transmit UE receive		Frequency band (MHz)	Duplex Mode
	F_{UL_low} – F_{UL_high}		F_{DL_low} – F_{DL_high}			
1	1920 MHz – 1980 MHz		2110 MHz – 2170 MHz		2,100	FDD
2	1850 MHz – 1910 MHz		1930 MHz – 1990 MHz		1,900	FDD
3	1710 MHz – 1785 MHz		1805 MHz – 1880 MHz		1,800	FDD
4	1710 MHz – 1755 MHz		2110 MHz – 2155 MHz		1,700	FDD
5	824 MHz – 849 MHz		869 MHz – 894MHz		850	FDD
6	830 MHz – 840 MHz		875 MHz – 885 MHz		850	FDD
7	2500 MHz – 2570 MHz		2620 MHz – 2690 MHz		2,600	FDD
8	880 MHz – 915 MHz		925 MHz – 960 MHz		900	FDD
9	1749.9 MHz – 1784.9 MHz		1844.9 MHz – 1879.9 MHz		1,800	FDD
10	1710 MHz – 1770 MHz		2110 MHz – 2170 MHz		1,700	FDD
11	1427.9 MHz – 1447.9 MHz		1475.9 MHz – 1495.9 MHz		1,500	FDD
12	699 MHz – 716 MHz		729 MHz – 746 MHz		700	FDD
13	777 MHz – 787 MHz		746 MHz – 756 MHz		700	FDD
14	788 MHz – 798 MHz		758 MHz – 768 MHz		700	FDD
15	Reserved		Reserved			FDD
16	Reserved		Reserved			FDD
17	704 MHz – 716 MHz		734 MHz – 746 MHz		700	FDD
18	815 MHz – 830 MHz		860 MHz – 875 MHz		850	FDD
19	830 MHz – 845 MHz		875 MHz – 890 MHz		850	FDD
20	832 MHz – 862 MHz		791 MHz – 821 MHz		800	FDD
21	1447.9 MHz – 1462.9 MHz		1495.9 MHz – 1510.9 MHz		1,500	FDD
22	3410 MHz – 3490 MHz		3510 MHz – 3590 MHz		3,500	FDD
23	2000 MHz – 2020 MHz		2180 MHz – 2200 MHz		2,000	FDD
24	1626.5 MHz – 1660.5 MHz		1525 MHz – 1559 MHz		1,600	FDD
25	1850 MHz – 1915 MHz		1930 MHz – 1995 MHz		1,900	FDD
26	814 MHz – 849 MHz		859 MHz – 894 MHz		850	FDD
27	807 MHz – 824 MHz		852 MHz – 869 MHz		850	FDD
28	703 MHz – 748 MHz		758 MHz – 803 MHz		700	FDD
29	N/A		717 MHz – 728 MHz		700	FDD2

30	2305 MHz	–	2315 MHz	2350 MHz	–	2360 MHz	2,300	FDD
31	452.5 MHz	–	457.5 MHz	462.5 MHz	–	467.5 MHz	450	FDD
...								
33	1900 MHz	–	1920 MHz	1900 MHz	–	1920 MHz	2,100	TDD
34	2010 MHz	–	2025 MHz	2010 MHz	–	2025 MHz	2,100	TDD
35	1850 MHz	–	1910 MHz	1850 MHz	–	1910 MHz	1,900	TDD
36	1930 MHz	–	1990 MHz	1930 MHz	–	1990 MHz	1,900	TDD
37	1910 MHz	–	1930 MHz	1910 MHz	–	1930 MHz	1,900	TDD
38	2570 MHz	–	2620 MHz	2570 MHz	–	2620 MHz	2,600	TDD
39	1880 MHz	–	1920 MHz	1880 MHz	–	1920 MHz	1,900	TDD
40	2300 MHz	–	2400 MHz	2300 MHz	–	2400 MHz	2,300	TDD
41	2496 MHz		2690 MHz	2496 MHz		2690 MHz	2,500	TDD
42	3400 MHz	–	3600 MHz	3400 MHz	–	3600 MHz	3,500	TDD
43	3600 MHz	–	3800 MHz	3600 MHz	–	3800 MHz	3,700	TDD
44	703 MHz	–	803 MHz	703 MHz	–	803 MHz	700	TDD
	NOTE 1: Band 6 is not applicable							
	NOTE 2: Restricted to E-UTRA operation when carrier aggregation is configured. The downlink operating band is paired with the uplink operating band (external) of the carrier aggregation configuration that is supporting the configured Pcell.							

Although some of these bands are already occupied by existing different IMT technologies, it could be used for an IMT-Advanced technologies by re-farming it in an appropriate way that will be suitable with each country, however, it should take into account the terminals manufacturing aspects, and the global harmonization for these bands.

By 2018, there will be eight major FDD bands or band groups. In order of addressable market size, and they will be: Band 7 (2600MHz); Band 3 (1800MHz); Band 4 (2100MHz AWS); Band 1 (2100MHz); Bands 12/13/14/17 (700MHz US); Band 20 (800MHz); Band 28 (700MHz APT); Band 2 (1900MHz), in addition to a TDD bands : Band 40 (2300MHz); Band 41 (2500MHz); Band 39 (1900MHz); Band 38 (2600MHz)[5].

FDD   TDD
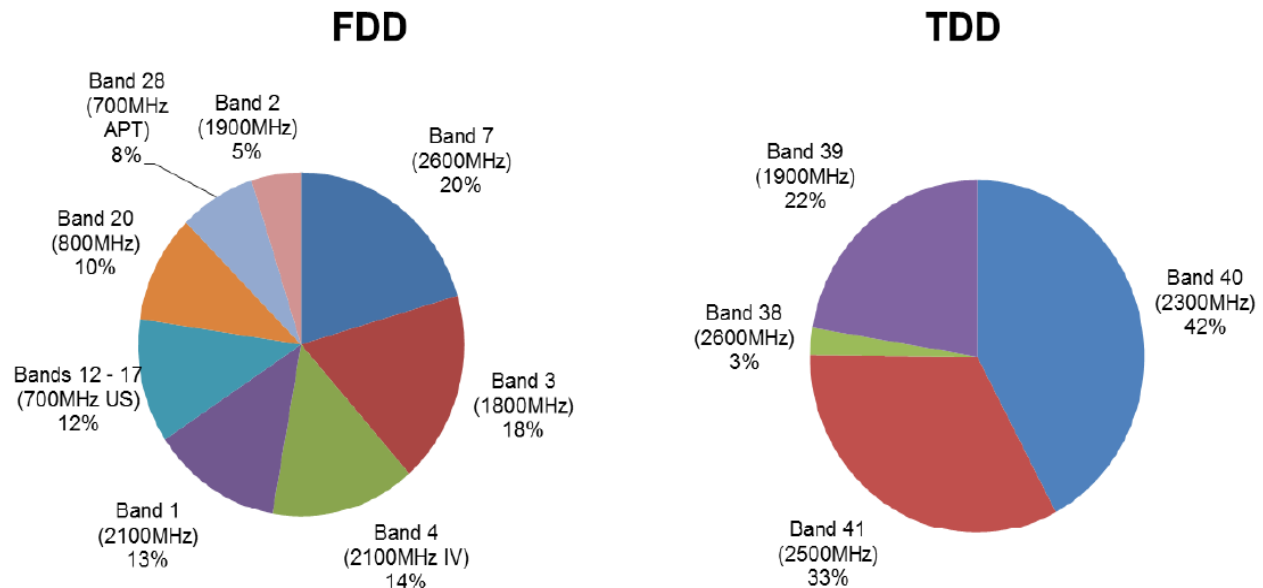
Source: Informa Telecoms & Media

Figure (2.3): Global addressable market share 2018, major bands

2.6 LTE Device Availability

As pointed earlier one of the other major factors that influence the decision of some countries regarding the suitable bands to be used is the manufacturing aspects. According to the statistics that made by Global mobile Suppliers Association (GSA) till January 2014 it confirm that there are 1,371 LTE user devices have been launched in the market by 132 suppliers , as shown in the figure below[6]:
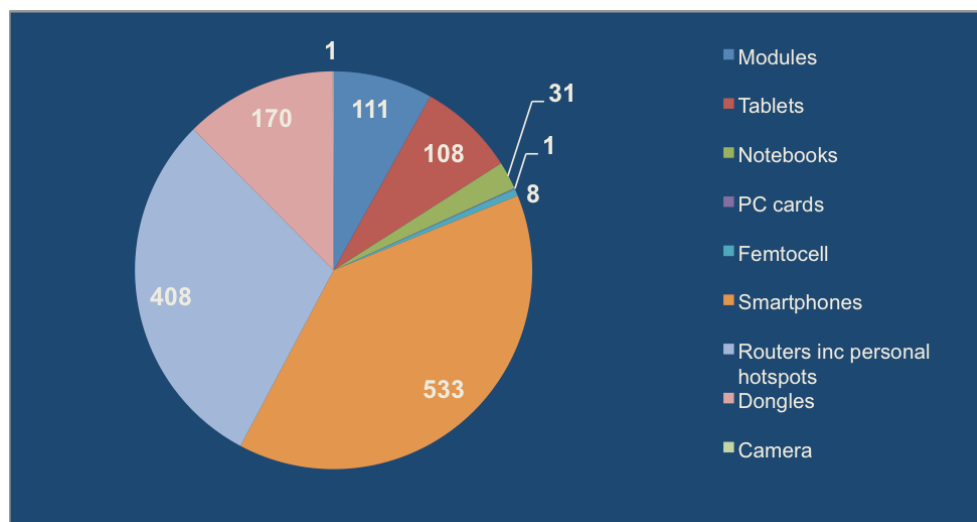
Source: GSA – Global mobile Suppliers Association

Figure (2.4): 1,371 LTE user devices - form factors

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We could notice that the smartphones are the largest LTE device category by a number of 533 smartphones including operator and frequency variants, representing 39% share of all LTE device types. Most devices operate in the FDD mode. However, 304 devices now support LTE TDD mode (TD-LTE). Several devices –Not only smartphones- had been manufactured to operate by multiband and/or multimode, as shown in the following tables:

Table (2.3): LTE FDD operating bands and number of manufactured devices that support this band

LTE band	Number of devices
2600 MHz band 7	493 devices
1800 MHz band 3	483 devices
2100 MHz band 1	354 devices
800 MHz band 20	335 devices
700 MHz bands 12 or 17	308 devices
700 MHz AWS band 4	303 devices
800/1800/2600 tri-band	298 devices
700 MHz band 13	261 devices
850 MHz band 5	243 devices
900 MHz band 8	205 devices
1900 MHz band 2	149 devices
1900 MHz band 25	92 devices

Table (2.4): LTE TDD operating bands and number of manufactured devices that support this band

LTE band	Number of devices
2600 MHz band 38	215 devices
2300 MHz band 40	207 devices
2600 MHz band 41	81 devices
1900 MHz band 39	80 devices
3500 MHz band 42,43	15 devices

2.7   The Future of 2G Networks

Although most of the manufacturers and industries currently focus on the mobile new technologies and the mobile broadband services, however most of the current global cellular connections still run on 2G networks and that is due to the increasing expansion of the developing countries in contrast to the global connections.

Although some of the mobile operators globally have already took a decision to re-farm the 2G spectrum for 3G and 4G technologies, but it is expected that the 2G networks will still important for the next couple years, due to many reasons [7]:

1. The 2G networks are already deployed nationwide, it has a high bandwidth and propagation, and it is very cost efficiency.
2. The Affordability of the 2G products and services.
3. Some Mobile Network Operators (MNOs) and Mobile Virtual Network Operators (MVNOs) still focus on the low-cost services.
4. Since the 3G/LTE networks coverage has not yet reached most of the population, so the existence of the 2G networks is still important for roaming activity.
5. Some regulatory obligations regarding the licenses and its duration.

So, due to all the above reasons it is expected that the 2G-only networks will still exist in the next few years, however it will start to vanish gradually with the time as some market researches expect.
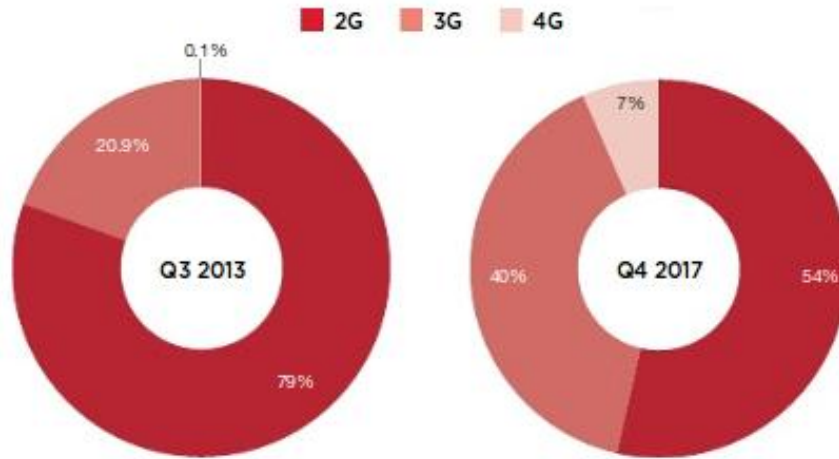
Figure (2.5): Network technologies as % of total connections in the developing world

2.8 **Calculation Methodology And Related Works**

To estimate the required spectrum for the Sudan to be able to use the IMT-Advanced technologies the SPECtrum requirement calcULATOR "SPECULATOR" model will be used.

The SPECULATOR model had been developed by the ITU-R, and it based on market survey data predicting the traffic load for different years, which had been approved as Recommendation ITU-R M.1768, and the input to the calculations includes market studies from Report ITU-R M.2072 as well as radio parameters from Report ITU-R M.2074 and Report ITU-R M.2290, and it will be explained in details in chapter 3.

This model had been used to calculate the IMT-Advanced spectrum requirements by several countries such as China [8], some leading telecommunication companies as Ericsson [9], and as well as by an individual researchers [10] [11] [12].

Spectrum Calculation Methodology

3.1   Introduction

As a preparation for the World Radiocommunication Conference 2007 (WRC-07) the ITU had developed a new methodology to calculate the spectrum requirements of the terrestrial component of the future development of IMT-2000 and IMT-Advanced. First contributions towards a new methodology were made by the Mobile IP-based Network Developments project (MIND) funded by the European Commission Information Society Technologies (IST) Framework Programme 5 (FP5) in 2002 (IST-MIND D3.3 2002). However, the methodology presented there did not meet with success, and new proposals for the development of the methodology were received at Working Party 8F of ITU-R (ITU-R WP 8F) in 2003–2005.

Continuation for the ITU methodology for estimation of spectrum requirements of IMT- 2000 was presented by Mohr (2003), where the impact of estimated data rate requirements on the spectrum requirements of future systems was examined. In Mohr (2003), the radio interface is described in a generic form based on a modified Shannon channel capacity equation, which is useful to obtain generalized results independent of the particular radio interface. By defining a relation between cluster size, carrier-to-interference ratio and coverage requirements, the spectrum requirement and system throughput can be calculated for a radio interface with and without adaptive modulation and coding.

The new spectrum calculation methodology, accepted by ITU, for the future development of IMT-2000 and IMT-Advanced which goes beyond IST-MIND D3.3 (2002) and Mohr (2003) is presented in IST-2003-50781 WINNER D6.2 (2005). The work on the spectrum calculation methodology by ITU-R WP 8F was completed in November 2005 when ITU-R Study Group (SG) 8 adopted the final Recommendation ITU-R M.1768. Before completion, the development of the methodology had continued within the ITU-R WP 8F for several years [13].

3.2 Calculation Methodology

To calculate the required spectrum for IMT-advanced systems, ITU-R has developed a new methodology based on market survey data predicting the traffic load for the year 2010 and beyond, which had been approved as Recommendation ITU-R M.1768.

The SPECtrum requirement calcULATOR "SPECULATOR" model will be used to estimate the required spectrum, it could be found in ITU study group 5 (SG5) 'http://www.itu.int/ITU-R/index.asp?category=study-groups&rlink=rsg5&lang=en' .

The methodology follows a deterministic flow, starting from the market predictions of the future mobile services and ending in the final spectrum requirements of pre-IMT, IMT-2000, future development of IMT-2000 and IMT-Advanced systems in the time span of years 2010–2020[13], however, here it will be customized and used to calculate the IMT-Advanced spectrum requirements only with a time-shift 5 years in the ITU market study.

The input to the calculations includes market studies from Report ITU-R M.2072 as well as radio parameters from Report ITU-R M.2074.

The calculation methodology takes into account the total mobile telecommunication market provided by various communication means. The methodology needs to be technology neutral and generic, and therefore the individual radio access techniques (RATs) are grouped into four RATGs such as presented in Report ITU-R M.2074, and four RATGs are [13]:

- RATG 1: Pre-IMT systems, IMT-2000, and its future development;
- RATG 2: IMT-Advanced systems, e.g. new mobile access and new nomadic/local area wireless access;
- RATG 3: Existing radio local area networks (RLANs) and their enhancements;
- RATG 4: Digital mobile broadcasting systems and their enhancements.

3.3 Methodology Flow Chart

The methodology follows a deterministic approach and consists of customized several steps starting from the market expectations of wireless communication services and ending in the final spectrum requirements such as shown in the Figure (3.1) below:

```
┌─────────────────────────────┐              ┌─────────────────────────────────┐
│ Collect all the required    │              │ Define service categories,      │
│ from the competent          │─────────────▶│ service environments,           │
│ authorities, analyze it and │              │ radio environments and RATGs    │
│ put it in the right form    │              │                                 │
└─────────────────────────────┘              └─────────────────────────────────┘
                                                            │
                                                            ▼
                                             ┌─────────────────────────────────┐
                                             │ Analyze collected market data   │
                                             └─────────────────────────────────┘
                                                            │
                                                            ▼
                                             ┌─────────────────────────────────┐
                                             │ Calculate traffic demand by     │
                                             │ service categories              │
                                             │ and service environments        │
                                             └─────────────────────────────────┘
                                                            │
                                                            ▼
                                             ┌─────────────────────────────────┐
                                             │ Distribute traffic between      │
                                             │ radio environments and          │
                                             │ RATGs, and calculate offered    │
                                             │ traffic                         │
                                             └─────────────────────────────────┘
                                                            │
                                                            ▼
                                             ┌─────────────────────────────────┐
                                             │ Calculate required system       │
                                             │ capacity to carry               │
                                             │ offered traffic for             │
                                             │ IMT-Advanced (RATG 2)           │
                                             └─────────────────────────────────┘
                                                            │
                                                            ▼
                                             ┌─────────────────────────────────┐
                                             │ Combine capacity requirements,  │
                                             │ and calculate                   │
                                             │ initial spectrum requirements   │
                                             └─────────────────────────────────┘
                                                            │
                                                            ▼
                                             ┌─────────────────────────────────┐
                                             │ Adjust the IMT-Advanced         │
                                             │ (RATG 2) spectrum               │
                                             │ requirements (multiple          │
                                             │ operators, round up to          │
                                             │ minimum spectrum)               │
                                             └─────────────────────────────────┘
                                                            │
                                                            ▼
                                             ┌─────────────────────────────────┐
                                             │ Calculate aggregate spectrum    │
                                             │ requirements of                 │
                                             │ all operators, add guard bands  │
                                             └─────────────────────────────────┘
                                                            │
                                                            ▼
                                             ┌─────────────────────────────────┐
                                             │ Calculate final spectrum        │
                                             │ requirements for IMT-           │
                                             │ Advanced for Sudan (Republic of)│
                                             └─────────────────────────────────┘
```
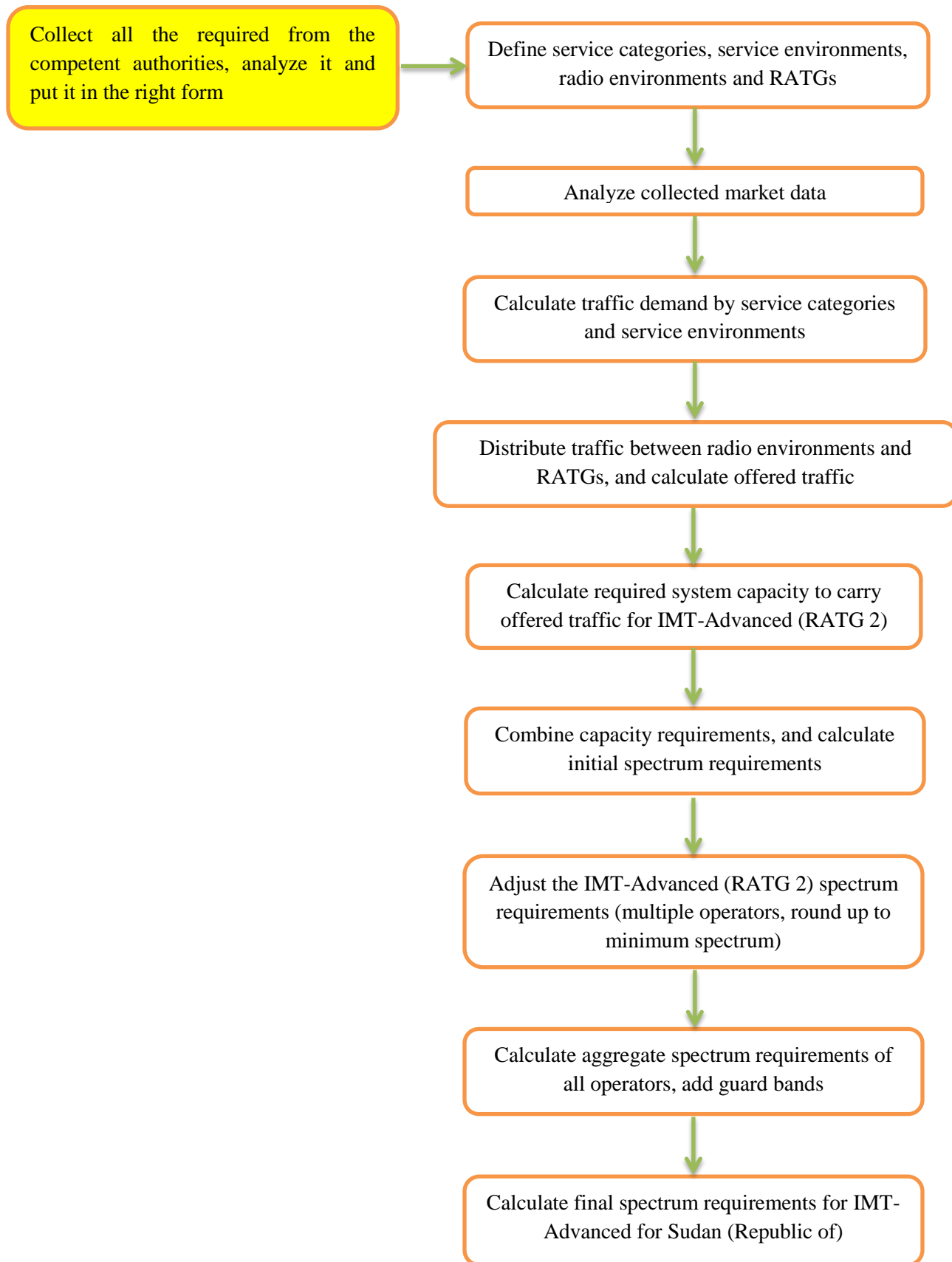
Figure (3.1): Methodology flow chart

After gathering the required data from the competent authorities, the data will be analyzed and organized in the right form to be use in the reference model, in addition to customize the model to be used for estimating only the IMT-Advanced spectrum for Sudan based on these given data and the nature of the IMT-Advanced technologies that could be deployed in the country.

The first step in the above Figure introduces the definitions of the different concepts used in the methodology, as well as the parameters used to characterize the concepts.

Second step in the methodology flow chart is to analyze the market data which is obtained from the market studies given in Report ITU-R M.2072. Then this data will be processed as the third step in order to obtain the traffic values for the service categories in different environments needed in the spectrum calculation methodology. In the fourth step, the total traffic of all mobile communication systems will be distributed to different radio environments (i.e. cell layers) and radio access techniques (RATs) which are presented as RAT groups (RATGs).

Starting from the fifth step and onwards all the calculations will be done for only RATG 2 which is corresponding to the IMT-Advanced systems. The fifth step is aim to determine the required system capacity to carry that offered traffic. The methodology uses separate capacity calculation algorithms for reservation-based and packet based services,

Then the spectrum requirements of RATG 2 will be calculated in the sixth step, after that a necessary adjustments will be applied to the spectrum results in step seven in order to take into account practical network deployments and to aggregate over the different spatially coexisting cell layers. The aggregate spectrum requirements of all operators are calculated in the step eight. And the ninth step is to obtain the final spectrum requirements of the IMT-Advanced by taking the maximum over spatially non-coexisting environments [13].

3.4 Model input parameters

This section will describe all the input parameters and relevant categorization. As shown in the Figure (3.1) above, the first step define the services categories, service environments, radio environments and RATGs.

3.4.1 Service Categories

3.4.1.1 Service Categories definition

A service category (SC) is defined as a combination of the service type and traffic class. This model applied the traffic classes that are presented in the ITU-R M.1079, which defines four quality of service (QoS) classes from the user perspective; the major different factor between these classes is the delay-sensitivity of the application [14]:

A. Conversational class of service:

The most well-known use of this scheme is telephony speech. But with internet and multimedia a number of new applications will require this scheme, for example voice over Internet Protocol (VoIP) and videoconferencing tools.

The maximum transfer delay is given by the human perception of video and audio conversation. Therefore the limit for acceptable transfer delay is very strict, as failure to provide low enough transfer delay will result in unacceptable lack of quality

B. Interactive class of service:

This scheme is applied when the end-user (either a human or a machine) is online and requesting data from remote place (e.g. servers),

The interactive class is also another classical data communication scheme that on an overall level is characterized by the request response pattern of the end-user. At the message destination there is an entity expecting the message (response) within a certain time. Round-trip delay time is therefore one of the key attributes. Another characteristic is that the content of the packets must be transparently transferred (with low BER).

C. Streaming class of service:

When the user is looking at (listening to) real-time video (audio) the scheme of real-time streams applies. The real-time data flow is always aiming at a live (human) destination. It is a one-way transport.

In this class the delay variation of the end-to-end flow must be limited, to preserve the time relation (variation) between information entities of the stream.

D. Background class of service:

This scheme is applied when the end-user, that typically a computer, sends and receives data-files in the background, such as delivery of e-mails, SMS, download of databases and reception of measurement records.

Although this class is a delay- insensitive, however there is still a delay constrains since the data could be useless if it is received too late. The only major requirement for applications in this class is that information should be delivered to the user essentially error free.

As mentioned earlier, the service category is defined as a combination of the service type and traffic class, as shown in Table (3.1) below:

Table (3.1): Service category number

Traffic class / Service type	Conversational	Streaming	Interactive	Background
Super high multimedia	SC 1	SC 6	SC 11	SC 16
High multimedia	SC 2	SC 7	SC 12	SC 17
Medium multimedia	SC 3	SC 8	SC 13	SC 18
Low rate data and low multimedia	SC 4	SC 9	SC 14	SC 19
Very low rate data[(1)]	SC 5	SC 10	SC 15	SC 20

[(1)] This includes speech and SMS.

The service type represents the peak data rates, the services that demanding similar data rate could be grouped together into a common category. The different services are divided into five service types as shown in Table (3.2) [14]:

Table (3.2) : Service types and their peak bit rates

Service type	Peak bit rate
Very low rate data	< 16 Kbit/s
Low rate data and low multimedia	< 144 Kbit/s
Medium multimedia	< 2 Mbit/s
High multimedia	< 30 Mbit/s
Super-high multimedia	30 Mbit/s to 100 Mbit/s 1 Gbit/s

Service categories 1– 10 (conversational and streaming traffic classes)are assumed to be served with circuit switching, while other service categories 11 - 20 (interactive traffic and background classes) are served with packet switching.

3.4.1.2   Service Category Parameters

Service categories are characterized with parameters which are obtained either from market studies or from other sources. The following parameters are obtained from Report ITU-R M.2072 [14]:

- User density (users/km^2).
- Session arrival rate per user (sessions/(s ·user)).
- Mean service bit rate (bit/s).
- Mean session duration (s/session).
- Mobility ratio.

The first four parameters characterize the demand of different service categories, while the mobility parameter is used in traffic distribution. Terminal mobility is closely related to application usage scenarios. Recommendation ITU-R M.1390 defines mobility as:

- In-building,
- Pedestrian,
- Vehicular.

The requirements depend upon the speed of the mobile stations. In market studies in Report ITU-R M.2072, the mobility classes are categorized as follows:

- Stationary (0 km/h)
- Low (> 0 km/h and < 4 km/h)
- High (> 4 km/h and < 100 km/h)
- Super-high (>100 km/h and < 250 km/h).

For small cells the cell size limits the maximum supported velocity. For this reason, pico cells are typically limited to support up to pedestrian velocities (up to 3-10 km/h), micro cells up to urban vehicular speeds of 50 km/h and macro cells of mobile cellular radio networks cover the remaining range of user velocity [14]. For application of the mobility classes in the methodology, the mobility classes from market studies are re-interpreted as follows:

– Stationary/Pedestrian (0-4 km/h)

– Low (> 4 km/h and < 50 km/h)

– High (> 50 km/h).

The traffic of the "high" mobility class that obtained from market studies is split into the "low" and "high" mobility classes. The splitting needs to take into account the attributes of the considered service environments which can result in different splitting factors J_m in different service environments m. The mapping of traffic to the mobility classes is presented in Tables (3.3) and (3.4) below [13]:

Table (3.3): Mapping of mobility class

Mobility in market study	Mobility in methodology
Stationary	Stationary/pedestrian
Low	
High	Low (fraction J_m)
	(fraction $1 - J_m$)
Super-high	High

Table (3.4): J-values for mapping of mobility classes in different service environments

Service environment m	J_m-value
1	1
2	1
3	1
4	1
5	0.5
6	0

3.4.2 Service Environments

Service environments (SEs) are used to characterize the different environments where the users exist. It is a combination of teledensity and service usage pattern.

Teledensities describe the population density in different areas. Three teledensities are considered in this model, including dense urban, suburban and rural. Teledensities are geographically non-overlapping areas while several service usage patterns can coexist in each teledensity, resulting in possibly several service environments in each teledensity.

Service usage patterns describe the user behavior. Three service usage patterns are considered, including home, office and public area [13].

This model considers six service environments, as shown in Table (3.5) below:

Table (3.5): The identification of Service Environments

Teledensities / Service usage patterns	Dense urban	Suburban	Rural
Home	SE 1	SE 4	SE 6
Office	SE 2	SE 5	
Public area	SE 3		

3.4.3 Radio Environments

Radio environments (REs) are defined by the cell layers in a network consisting of hierarchical cell layers, i.e. macro cell, micro cell, Pico cell and hot spot. Radio environments are the areas exhibiting common propagation and deployment conditions [13]. And they are characterized by two parameters:

- Cell area (km^2/cell)
- Population coverage percentage (%).

The population coverage percentage denotes the ratio of population that lives in the service area of a given radio environment in a given service environment.

In addition to all the above categories and environments parameters, the model deals with another market data which includes the traffic forecasts covering the whole market of mobile telecommunications in the years 2010, 2015 and 2020.however, to apply it in our customized model has been used with 5 years' time-shift in order to get an optimum results in our case. The

market data is needed for the following parameters: user density, session arrival rate per user, average session duration, mean service bit rate and mobility ratios for different service categories in different service environments in different forecast years [13]. A comprehensive collection of market studies are provided by the ITU-R in the Report ITU-R M.2072.

All the above input parameters could be summarized in the following Figure (3.2) [13]:

Market study parameters	Other service category parameters	Radio-related parameters	Other parameters
User density (users/km^2)	Mean packet size (bit/packet)	Cell area (km^2/cell)	Population coverage percentage (%)
Session arrival rate per user (sessions/s/user)	Second moment of packet size (bit^2/packet^2)	Spectral efficiency (bit/s/Hz/cell)	Traffic distribution ratio among available RATGs
Average session duration (s/session)	Maximum allowable mean packet delay (s/packet)	Number of overlapping network deployments	Radio environment definition
Mean service bit rate (bit/s)	Maximum allowable blocking probability (%)	Minimum spectrum deployment (MHz)	
Mobility ratio (stationary, low, high, and super-high)	Capacity calculation	Guard band between operators (MHz)	RATG 1 and RATG 2
Traffic volume calculation		Application data rate (bit/s)	
		Support for multicast (yes/no)	RATG 3 and RATG 4
		Maximum supported velocity (km/h)	

Figure (3.2): Input parameters for ITU spectrum calculation methodology

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3.5 Model Traffic Distribution

The methodology used in this thesis processes the market study traffic volumes to predict the traffic demand, data rates and user mobility. It distributes the traffic from the market studies to All RATGs and radio environments using technical and market related information and hence calculate the capacity requirements for our require RATG (RATG 2). Then the capacity requirements are processed with the spectral efficiency values to obtain the initial spectrum requirements, and then deal with other factors related to the practical number of deployments to adjust the spectrum requirements.

Traffic distribution and spectrum requirement calculations could be summarized in the following Figure (3.3) [13]:
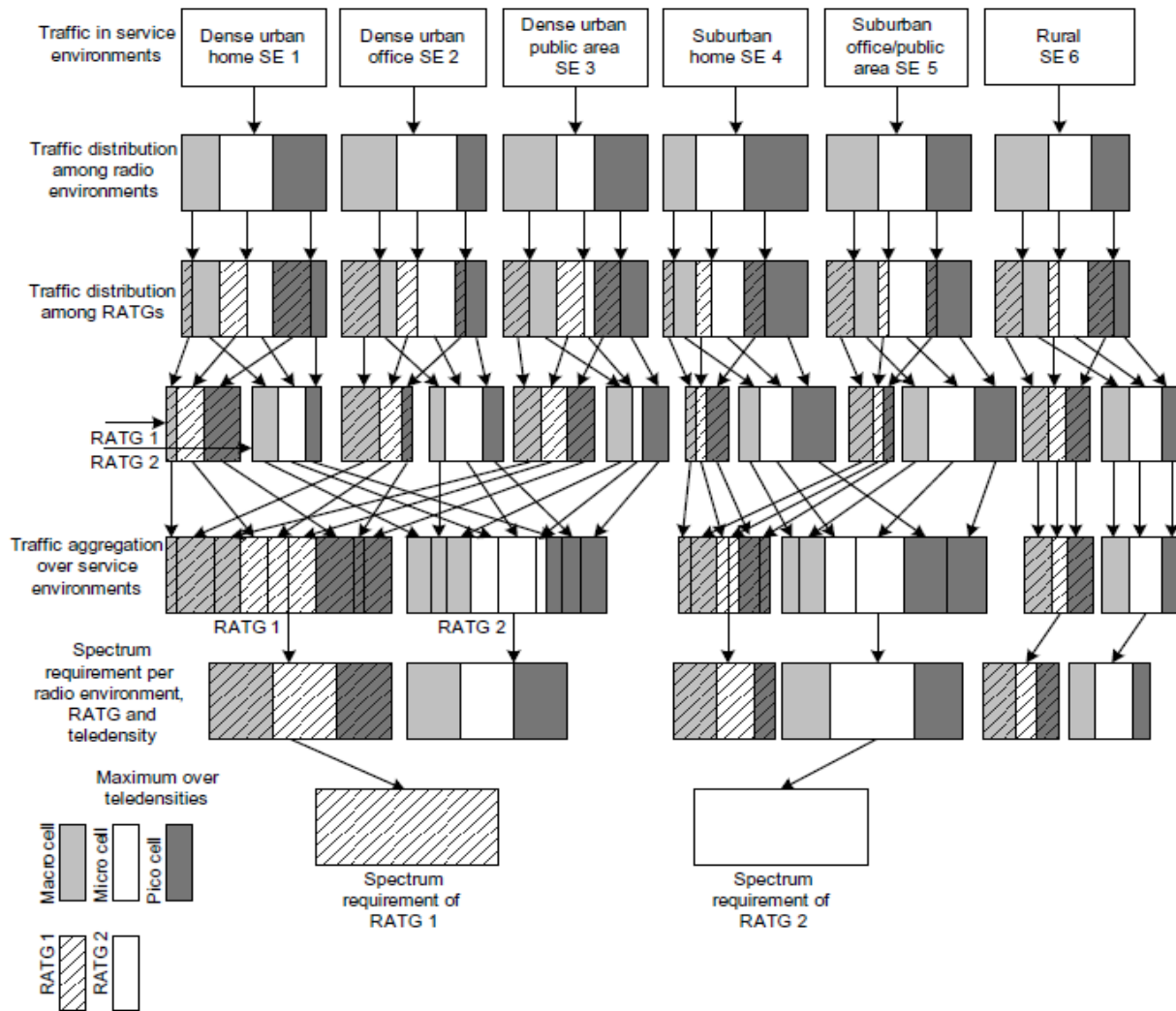
Figure (3.3): Traffic distribution and spectrum requirement calculation

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3.6   SPECULATOR Tool Description

The SPECULATOR model had been implemented in MS Excel software and available publicly in the ITU website 'http://www.itu.int/ITU-R/studygroups/docs/speculator.doc'. This tool consists of 27 worksheets and 7 modules of macros. It includes input parameter values, intermediate calculation results from spreadsheet calculations and macro calculations, and final spectrum requirements with some charts.

The SPECULATOR tool includes input parameters from report ITU-R M.2078, and the market data from report ITU-R M.2072. And it can be divided into four parts: front sheet, input parameters, intermediate calculations and outputs.

3.7   SPECULATOR Model Calculations

The SPECULATOR model calculations methodology includes traffic calculations and distribution, capacity requirement calculations and finally spectrum requirement calculations based on the above described service categories, service environments and radio environments and their parameters[1].

3.7.1 Calculation of Traffic Demand from Market Data

As mentioned earlier, the market data includes the traffic forecasts covering the whole market of mobile telecommunications in the years 2010, 2015 and 2020.however, to apply it in our customized model has been used with 5 years' time-shift in order to get the results in our case. The market data is needed for the following parameters: user density, session arrival rate per user, average session duration, mean service bit rate and mobility ratios for different service categories in different service environments in different forecast years.

The market data are given for service category and service environment for all forecast years separately for uplink and downlink directions as well as for unicast and multicast traffic.

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[1] All the equations in this section are taken from "*Spectrum Requirement Planning in Wireless Communications: Model and Methodology for IMT-Advanced* ".

Now assume that:

❖ $U_{m,n} \equiv$ user density of service category n in service environment m (users/km^2);

❖ $Q_{m,n} \equiv$ session arrival rate per user of service category n in service environment m (sessions/s/user);

❖ $\mu_{m,n} \equiv$ average session duration of service category n in service environment m (s/session);

❖ $r_{m,n} \equiv$ mean service bit rate of service category n in service environment m (bit/s).

And the market study mobility ratios for stationary, low, high and super-high mobilities are:

❖ $MR_{stat/ped;m,n} \equiv$ stationary/pedestrian mobility ratio of service category n in service environment m;

❖ $MR_{low;m,n} \equiv$ low mobility ratio of service category n in service environment m;

❖ $MR_{high;m,n} \equiv$ high mobility ratio of service category n in service environment m.

Then the mobility ratios taking a value between 0 and 1, and it should sum to one:

$$MR_{stat/ped;m,n} + MR_{low;m,n,} + MR_{high;m,n} = 1 \qquad (3.1)$$

3.7.2 Traffic Distribution

As a fourth step in the methodology, the traffic will be distributed for each service category in each service environment to different RATGs and radio environment, and it perform separately for unicast and multicast as well as for uplink and downlink.

3.7.2.1 Unicast traffic

Assume that the traffic distribution ratio for unicast is denoted by $\xi_{m,n,rat,p}$, if all traffic can be distributed, the sum of traffic distribution ratios is equal to one:

$$\sum_{rat} \sum_p \xi_{m,n,rat,p} = 1 \qquad (3.2)$$

There are certain radio environments can support certain mobility classes, in this methodology the following mapping of mobility classes to radio environments are used:

• High mobility: macro cell only;

• Low mobility: micro and macro cells;

- Stationary/pedestrian: all radio environments.

Let us denote the population coverage percentage for each radio environment by $X_{hs;m}$, $X_{pico;m}$, $X_{micro;m}$ and $X_{macro;m}$, and noting that $X_{macro;m}= 1$, then the following algorithm is used:

$$\xi_{\text{pico\&}hs\ ;m,n} = \min\{X_{pico;m} + X_{hs;m} + MR_{stat/ped;m,n}\} \tag{3.3}$$

$$\xi_{\text{micro}\ ;m,n} = \min\{X_{micro;m}, MR_{low;m,n} + (MR_{stat/ped;m,n} - \xi_{\text{pico\&}hs\ ;m,n})\} \tag{3.4}$$

$$\xi_{\text{macro}\ ;m,n} = 1 - \xi_{\text{pico\&}hs\ ;m,n} - \xi_{\text{micro}\ ;m,n} \tag{3.5}$$

Then the traffic will be further distributed between hot spots and pico cells in proportion to their population coverage percentages as follow:

$$\xi_{hs\ ;m,n} = \xi_{\text{pico\&}hs\ ;m,n} \cdot \frac{X_{hs;m}}{X_{pico;m} + X_{hs;m}} \tag{3.6}$$

$$\xi_{pico\ ;m,n} = \xi_{\text{pico\&}hs\ ;m,n} \cdot \frac{X_{pico;m}}{X_{pico;m} + X_{hs;m}} \tag{3.7}$$

And it is then obvious

$$\sum_{p} \xi_{p\ ;m,n} = 1$$

$$\xi_{m,n,rat,p} = \xi_{p\ ;m,n} \cdot \xi_{rat} \tag{3.8}$$

Where ξ_{rat} is the distribution ratio among all the RATG. And since:

$$\sum_{rat} \xi_{rat} \leq 1$$

Then

$$\sum_{rat} \xi_{m,n,rat,p} \leq \xi_{p\ ;m,n}$$

3.7.2.2 Multicast Traffic

The multicast calculation process is similar to unicast, however, it takes into account whether the given RATG can support multicast traffic or not, which is determined by radio-related parameter 'support for multicast'.

The traffic distribution ratios for multicast traffic are determined by choosing the largest available cell for each service category with multicast traffic for each RATG in each service environment and forecast year. The final distribution ratio is set equal to '1' to the largest cell of each RATG fulfilling the requirements while the other available combinations are turned to '0'[13].

$$\xi_{m,n,rat,p}^{Multicast} = \begin{cases} 1 \ for \ p \ with \ largest \ cell \ size \\ 0 \ for \ other \ p. \end{cases} \tag{3.9}$$

$$\sum_p \xi_{m,n,rat,p}^{Multicast} = 1$$

$$(3.10)$$

3.7.3 Calculation of Offered Traffic

As a complimentary process to the fourth step, and after distributing the traffic volume for different RATGs and service environments, then the offered traffic will be calculated per each cell in each service category, each teledensity, each RATG, and each radio environments.

3.7.3.1 Session Arrival Rate per Cell

The session arrival rate will be calculated per cell (sessions/s/cell), and this will be done separately for unicast and multicast. For unicast:

$$P_{m,n,rat,p} = \xi_{m,n,rat,p} \cdot U_{m,n} \cdot Q_{m,n} \cdot A_{d,p} \tag{3.11}$$

Where:

- ❖ $U_{m,n}$ ≡ user density of service category n in service environment m (users/km^2);
- ❖ $Q_{m,n}$ ≡ session arrival rate per user of service category n in service environment m (sessions/s/user);
- ❖ $A_{d,p}$ ≡ cell area (km^2/cell) of radio environment p in teledensity d.
- ❖ $\xi_{m,n,rat,p}$ ≡ traffic distribution ratio.

In Multicast traffic, and since the traffic is transmitted using a shared radio resource to multiple receivers simultaneously. We may assume that there is a single user in a cell:

$$U_{m,n} \cdot A_{d,p} = 1 \tag{3.12}$$

And the session arrival rate per cell:

$$P_{m,n,rat,p} = \xi_{m,n,rat,p}^{Multicast} \cdot Q_{m,n} \tag{3.13}$$

3.7.3.2 Offered traffic and mean service bit rate for circuit-switched service categories

For circuit-switched service categories (SC1-SC10), the aggregate offered traffic per cell (Erlang/cell) will be calculated by:

$$\rho_{d,n,rat,p} = \sum_{m \in d} P_{m,n,rat,p} \cdot \mu_{m,n} \tag{3.14}$$

And the average values for the mean service bit rate (bit/s):

$$r_{d,n,rat,p} = \frac{\sum_{m \in d} P_{m,n,rat,p} \cdot \mu_{m,n} \cdot r_{m,n}}{\rho_{d,n,rat,p}} \tag{3.15}$$

Where:

❖ $r_{m,n}$ ≡ mean service bit rate(bit/s).

3.7.3.3 Offered Traffic for Packet-Switched Service Categories

For packet-switched service categories (SC11-SC20), the aggregate offered traffic per cell (bit/s/cell) will be calculated by:

$$T_{\text{d,n,rat,p}} = \sum_{m \in d} P_{\text{m,n,rat,p}} \cdot \mu_{\text{m,n}} \cdot r_{\text{m,n}}$$

<div align="right">(3.16)</div>

3.7.4 Required Capacity Calculations

The fifth step of the methodology is to calculate the required system capacity needed based on the offered traffic for each cell while fulfilling the QoS requirements. The required system capacity calculated for circuit-switched service categories and packet-switched service categories severally with different complex equations for each one, and getting the final required system capacity $C_{\text{d,rat,p}}^{\text{cs}}$(bit/s/cell) for circuit-switched service categories, and $C_{\text{d,rat,p}}^{\text{ps}}$(bit/s/cell) for packet-switched service categories.

3.7.5 Spectrum Results

The capacity requirements are processed as a sixth step in the methodology flow chart for each of circuit-switched service categories and packet-switched service categories for unicast and multicast. The total sum up of uplink and downlink:

$$C_{\text{d,rat,p}}^{\text{cs}} = C_{\text{d,rat,p,uplink}}^{\text{cs}} + C_{\text{d,rat,p,downlink}}^{\text{cs}}$$

$$C_{\text{d,rat,p}}^{\text{ps}} = C_{\text{d,rat,p,uplink}}^{\text{ps}} + C_{\text{d,rat,p,downlink}}^{\text{ps}} \qquad (3.17)$$

Then the total capacity requirement$C_{\text{d,rat,p}}$ (bit/s/cell) of all service categories can be obtained by adding the above total capacities:

$$C_{\text{d,rat,p}} = C_{\text{d,rat,p}}^{\text{cs}} + C_{\text{d,rat,p}}^{\text{ps}} \qquad (3.18)$$

By dividing the capacity requirement over corresponding spectral efficiency values we can get the spectrum requirements $F_{\text{d,rat,p}}$ (Hz):

$$F_{\text{d,rat,p}} = C_{\text{d,rat,p}}/\eta_{\text{d,rat,p}} \qquad (3.19)$$

Where:

❖ $\eta_{\mathrm{d,rat,p}} \equiv$ Area *spectral efficiency* (bit/s/Hz/cell).

In case of multicast capacity requirements, the corresponding spectrum requirement $F_{d,rat,p}^{multicast}$ is calculated separately and then added it to the unicast spectrum requirements:

$$F_{\mathrm{d,rat,p}} \leftarrow F_{\mathrm{d,rat,p}} + F_{d,rat,p}^{multicast} \tag{3.20}$$

Then necessary adjustments will be applied to the spectrum requirements as the seventh step, such as minimum spectrum deployment per operators and number of overlapping networks. The unadjusted spectrum requirement per operator is calculated from:

$$F_{\mathrm{d,rat,p}} \leftarrow F_{\mathrm{d,rat,p}}/N_o \tag{3.21}$$

Where:

❖ $N_o \equiv$ Number of overlapping networks.

Spectrum can only be used with the granularity of the minimum spectrum deployment per operator and radio environment which is denoted as $MinSpec_{rat,p}$(Hz). The spectrum requirement is adjusted with the minimum spectrum deployment according to [13]:

$$F_{\mathrm{d,rat,p}} = MinSpec_{rat,p}\lceil F_{\mathrm{d,rat,p}}/MinSpec_{rat,p}\rceil \tag{3.22}$$

Where $\lceil x \rceil$ denotes the least integer greater than or equal to x (ceiling function).

Then the spectrum requirements will be aggregated over different radio environments as the eighth step. The pico and hotspot will be assumed to be spatially non-coexisting. And the spectrum requirement $F_{\mathrm{d,rat}}$ over the different teledensities will be as modified in WP5D #14th meeting:

$$F_{\mathrm{d,rat}} = \max\{F_{\mathrm{d,rat,macro}}, F_{\mathrm{d,rat,micro}}\} + \max\{F_{\mathrm{d,rat,pico}}, F_{\mathrm{d,rat,hs}}\} \tag{3.23}$$

And the total required spectrum for all operators including the guard bands between operators becomes:

$$F_{\mathrm{d,rat}} \leftarrow N_o \cdot F_{\mathrm{d,rat}} + (N_o - 1) \cdot F_{rat}^G \tag{3.24}$$

Where:

❖ $F_{rat}^G \equiv$ the guard band between operators

And the final step in the methodology is to take the maximum spectrum requirements over the different teledensities F_{rat} (Hz):

$$F_{d,rat} = \frac{max}{d} \ F_{d,rat} \tag{3.25}$$

Results and Discussion

In this section, the results from SPECULATOR model are provided, Which had been adopted to meet the Sudan requirements with different scenarios (according to the number of operators that's may be ready to use this technology during this period), with a precaution to any new entrants in the future, and also for any other services that may use IMT-Advanced technologies.

4.1   Model Input Parameters

The parameter values presented in Report ITU-R M.2078 are used as the starting point, with changing in some input parameter values to familiarizing the model with Sudan market situations and forecasts.

Due to Sudan relatively small population in comparison with many other countries, and the horizontally distribution of this population, which yields to a small user density in each area, we will consider that the telecommunication market in Sudan is a lower user density market.

The other changed input parameters will be as follows:

4.1.1 Market Settings

To adopt the model we select Khartoum as the most urban area in Sudan, and then estimate the population density of the mobile subscribers with the help of the national telecommunication corporation (NTC) telecommunications indicators survey, and the percentage of mobile subscribers density for RATG2 forecasted to be as follow:
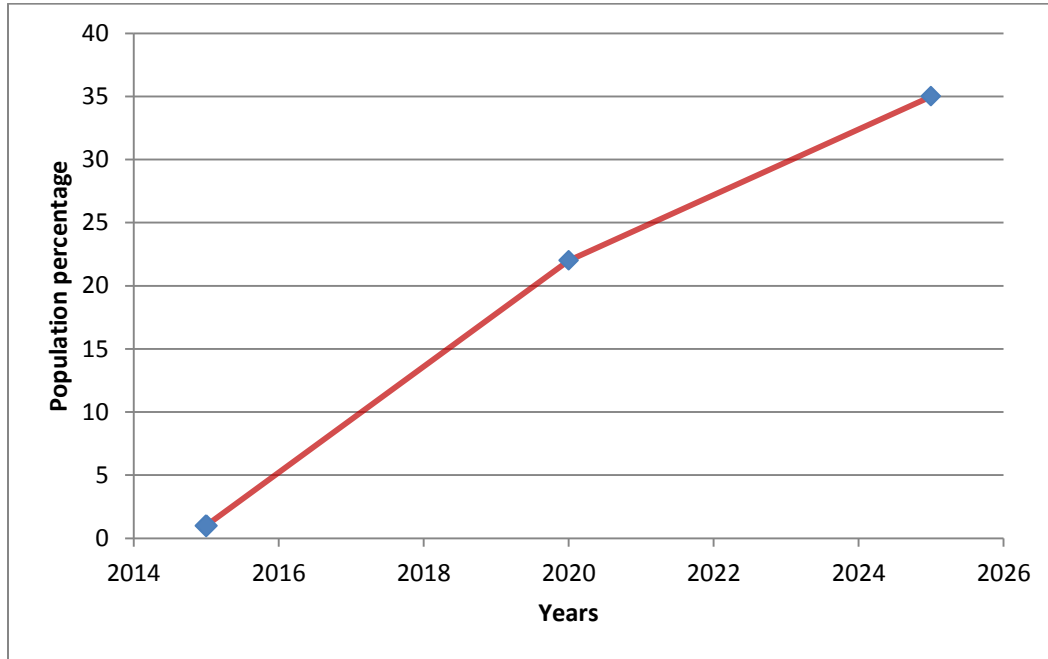
Figure (4.1): forecasted mobile subscribers percentages for RATG2

And it used in the model as follows:

Table (4.1): Sudan market attributes in 2015

SC	U (%)	Q (%)	R (%)	μ (%)	Mobility Ratio
From 1 to 20	1	40	40	40	2

where:

❖ $U \equiv$ user density (users/km^2);

❖ $Q \equiv$ session arrival rate per user (sessions/s/user);

❖ R ≡ mean service bit rate (bit/s).

❖ μ≡ average session duration (s/session);

The values of these parameters represent the weight of the market input parameters to calculate the current values of these parameters.The user density percentage forecasted to grow up to 22% in 2020, and up to 35% in 2025.

4.1.2 Service Environments

The population coverage percentage denotes the ratio of the population that is in the service area of a given radio environment in a given service environment. It puts a limit to the fraction of traffic that can be distributed to a given radio environment [21].

Table (4.2): Population Coverage Percentage in 2015

Service environments	Radio environments supporting service environment			
	Macro cell	Micro cell	Pico cell	Hot spot
SE1	100	1	0	0
SE2	100	2	1	0
SE3	100	2	1	0
SE4	95	0	0	0
SE5	90	0	0	0
SE6	80	0	0	0

Table (4.3): Population Coverage Percentage in 2020

Service environments	Radio environments supporting service environment			
	Macro cell	Micro cell	Pico cell	Hot spot
SE1	100	1	0	0
SE2	100	7	4	0
SE3	100	7	4	0
SE4	100	0	0	0
SE5	100	0	0	0
SE6	90	0	0	0

Table (4.4): Population Coverage Percentage in 2025

Service environments	Radio environments supporting service environment			
	Macro cell	Micro cell	Pico cell	Hot spot
SE1	100	1	0	0
SE2	100	12	10	0
SE3	100	12	10	0
SE4	100	0	0	0
SE5	100	0	0	0
SE6	100	0	0	0

4.1.3 Radio-related Input Parameters

4.1.3.1 Cell Area

Table (4.5): Modified Cell Areas

SECTOR AREA [km^2]			
Radio environment	**Teledensity**		
	DU	SU	RU
Macro cell	0.1	0.21666667	42.46666667
Micro cell	0.03466667	0.1	3.466666667
Pico cell	0.00216667	0.00866667	0.034666667
Hot spot	0.00216667	0.00866667	0.034666667

4.1.3.2 Other Radio-related Input Parameters

"Minimum deployment per operator per radio environment" represent the minimum spectrum required by the operator to build a real network for the given technology.

Noting that the application data rates increase with the time for small cells to meet the required data rates for the future IMT-Advanced specifications.

Table (4.6): Required Radio Parameters for RATG 2

Attribute	Unit	Value			
		Macro cell	Micro cell	Pico cell	Hot spot
Application data rate	[kbit/s]	100000	100000	100000	100000
Maximum supported velocity	[km/h]	250	50	4	4
Guard band between operators	[MHz]	0			
Minimum deployment per operator and radio environment	[MHz]	20	20	20	20
Number of overlapping network deployment	#	1			
Support for multicast (yes=1, no=0)		1			

4.2 Model Output Results

The output results from the model represent the amount of spectrum needed to deploy the IMT-Advanced technologies in Sudan in acordance to the above customized input parameters. Figures below present the results from SPECULATOR model:
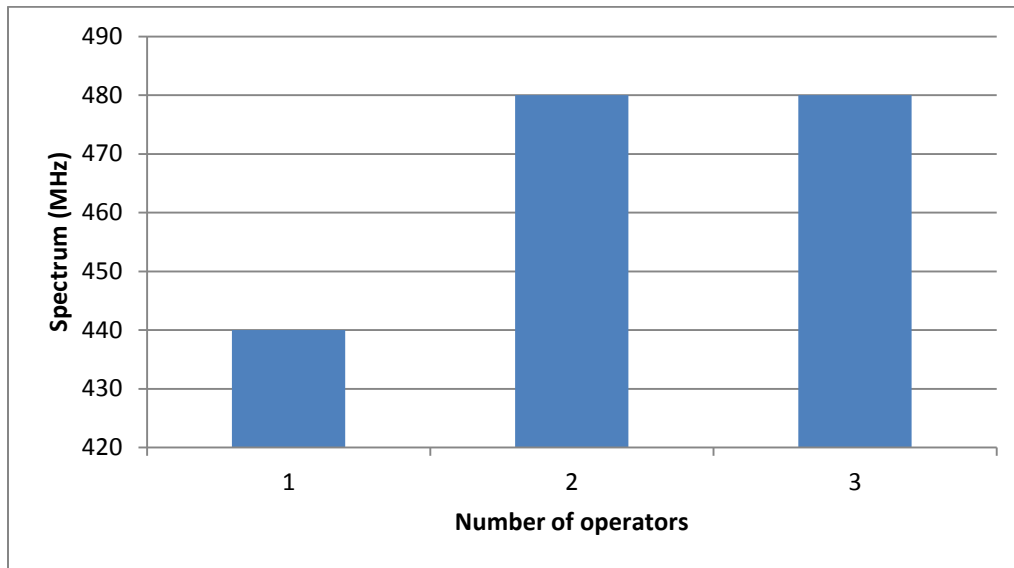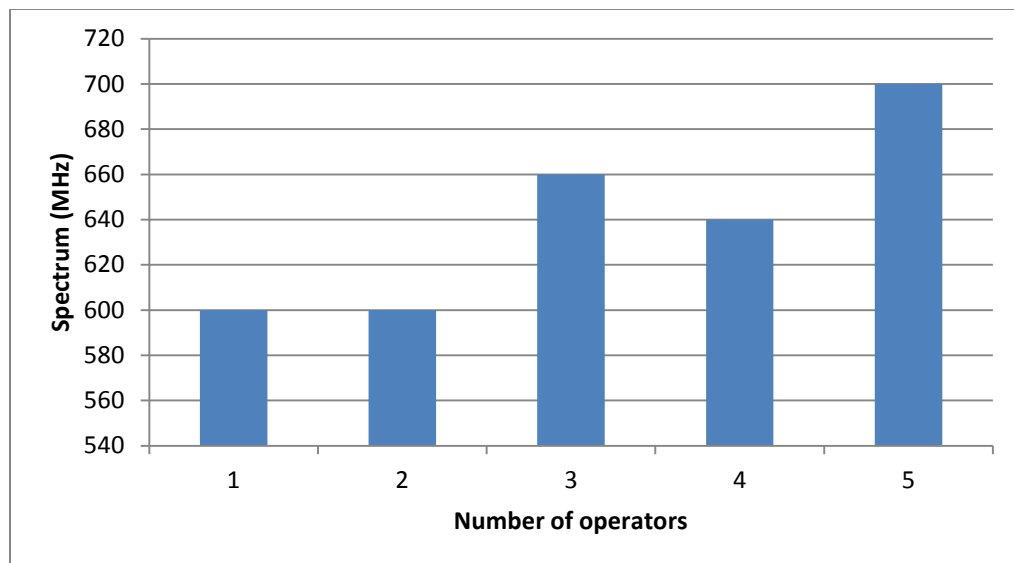

Figure (4.2): Required spectrum results for 2015

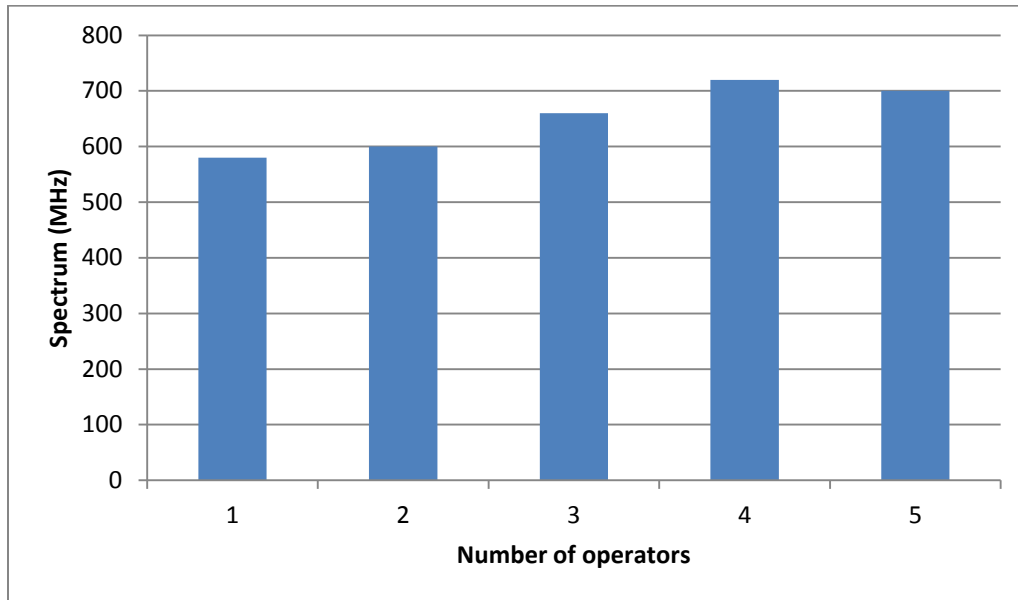Figure (4.3): Required spectrum results for 2020

Figure (4.4): Required spectrum results for 2025

We could notice that the number of operators in 2015 are just 3 operators, because it is the currently existing operators, and they may launch just a trial LTE networks, with no expectation to any new entrant this year.

From the above figures the maximum output required spectrum from the SPECULATOR model for RATG 2 is 720MHz, and then the total spectrum will be:

Table (4.7): Total spectrum requirements for RATG 1 and RATG 2

Current spectrum for RATG 1	Spectrum requirements for RATG 2	Total spectrum for RATGs 1 and 2
571 MHz	720 MHz	1291 MHz

From the input parameters it could be noticed that the number of population covered by a small cells now in Sudan is very small, and it will increase with the time, however this percentage of coverd population is not excpected to be like many other countries due to the small and horizontal distribution of the population.

It should be noted that its not necessary that the spectrum requirements going by an increasingly maner with time, althogh the traffic volume will increase, however the number of population that covered by a small cells will also increase with the time.

CHAPTER FIVE

Conclusion and Recommendations

5.1   Conclusion

The spectrum requirements estimation for IMT-advanced is a very important issue for both of the operators and the regulatory body of the country. But in fact it's more important for the regulatory body than the operator because it's responsible for laying down the plans, policies, regulations, allocation and licensing for the provision of the telecommunication services.

By determining our technology requirements, and studying our market behavior and forecast their needs in the future, we had been able to customize a model to estimate the required spectrum for the Sudan to be able to use the IMT-Advanced technologies till 2025 with different scenarios.

To estimate the required spectrum the ITU-R SPECtrum requirement calcULATOR "SPECULATOR" model was used, which is based on market survey data predicting the traffic load for different years, and it had been customized to meet the Sudan market situationsand forecasts.

The results of this model are presented in chapter 4, which illustrate the required spectrum with different scenarios (according to the number of operators), with a precaution to any new entrants in the future, and any other services that may use IMT-Advanced technologies during this period till 2025.

By estimating the required spectrum we help solving some of the technologies deployment implications which is the regulatory implication, since it is essential that radio spectrum planning and allocation strategies recognise the future requirements of the networks, however, there are many other issues have to be considered.

5.2 Recommendations

After estimating the required spectrum, the next step will be to choose the appropriate bands to be allocated for these technologies, taking into account nature of the country, and the terminals manufacturing aspects to ensure that the consumers getting access to best quality mobile services, cheapest possible handsets, and the global harmonization for these bands to maximizing their opportunities to experience cross-country mobility.

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