



**IMPROVING SPECTRUM EFFICIENCY IN TELEVISION BROADCASTING USING
SINGLE FREQUENCY NETWORK**

Christian TUYISHIME AHORANAYEZU

College of Science and Technology

School of Information and Communication Technology

Master of Science Degree in Operational Communication

2017



**IMPROVING SPECTRUM EFFICIENCY IN TELEVISION BROADCASTING USING
SINGLE FREQUENCY NETWORK**

By

Christian TUYISHIME AHORANAYEZU

REG. NO: 216366739

A dissertation submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE DEGREE IN OPERATIONAL COMMUNICATION

In the College of Science and Technology

Supervisor: Dr Said RUTABAYIRO NGOGA

June, 2017

DECLARATION

I, **Christian TUYISHIME AHORANAYEZU** declare that this Dissertation contains my own work and is the result of my own research; it has never been presented in other University or Higher Learning institutions, all texts and results which have been obtained from other sources/workers are fully referenced.

I understand that cheating and plagiarism constitute a breach of University regulations and will be dealt with accordingly;

Christian TUYISHIME AHORANAYEZU

Reg. No: 216366739

Signature.....

Date.....

Declaration by the supervisor(s)

I confirm that the work reported in this thesis was carried out by the candidate under my supervision.

Supervisor(s)

Name: Dr. Said RUTABAYIRO

Signature:

Date

ACKNOWLEDGMENT

I would like to acknowledge and give thanks in a special way to the Lord our God, from whom all knowledge, wisdom and understanding rightly comes, for all that He has so graciously allowed me to achieve.

I am most grateful to my Supervisor, Dr. Said RUTABAYIRO who supervised this work and offered all the necessary guidance and support during the entire course of this project.

My special thanks go to the lecturers of Master of Science in Operational Communications at College of Science and Technology (CST) for their effort and my classmates who helped in one way or another during the assignments.

My sincere thanks further goes to my wife Mrs. Alice UWIMANA for her spiritually and courage support during the two years course.

My gratitude thanks go also to Rwanda Utilities Regulatory Authority, my employer who financed me for taking the course and gave me regular authorization of attending classes.

Finally, to all my families and friends, there are no profound words to express my gratitude for the love and support that you have given me. It is therefore for lack of a better word that we only say thank you.

ABSTRACT

The increased demand for mobile broadband has recently led to the increase in demand of more radio spectrum for mobile services. Although the spectrum demand is increasing, frequency spectrum as resource itself is not increasing which lead to its scarcity.

World Radiocommunication Conference of 2007 (WRC-07) resolved that TV Broadcasting Services shall be digitalized by 2015, and release a big portion of the initially allocated spectrum to TV Broadcasting to be further used by other services and mainly mobile broadband services. Since then, much effort has been invested to improve and promote the use of different digital TV technologies such as DVB-T in Europe and part of Africa, ATSC in North America, ISDB-T in South America and DMB-T/H in Asian countries in order to meet the requirements and the deadline set by the International Telecommunication Union.

With this trend, Rwanda migrated to Digital Broadcasting in July 2013 and all analogue broadcasting transmitters were switched off. However, the MFN technology adopted in Rwanda have not addressed the problem of scarcity due to the fact that in MFN each site should have a different frequency from neighboring sites while the number of available frequencies is low compared to the increase in number of TV program to be carried on the TV Network.

This thesis study and propose a concept of single frequency network for TV Broadcasting in order to ensure an effective and efficient use of available spectrum. SFN used an OFDM scheme that allows all transmitters in a radio network to transmit identical signals in the same frequency block.

The study shows as well the improvement achieved in spectrum efficiency using the Single Frequency Network, and provides part of the finding in a simulation format.

KEY WORDS

Single frequency networks, multiple frequency networks, Orthogonal Frequency Division Multiplexing, Guard Interval, Symbol rate, terrestrial digital video broadcasting, analog broadcasting, and international telecommunication union

LIST OF SYMBOLS AND ACRONYMS

AM	Amplitude Modulation
ATSC	American Television Standards Committee's
BW	Bandwidth
DAB	Digital Audio Broadcasting
DVB	Digital Video Broadcasting
DTT	Digital Terrestrial Broadcasting
ERP	Effective Radiated Power
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
HDTV	High-Definition Television
HF	High Frequency
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
MFN	Multiple Frequency Network
MPEG	Motion Pictures Experts Group
SFN	Single Frequency Network
OFDMA	Orthogonal Frequency Division Multiple Access
PAL	Phase Alternating Line
RBA	Rwanda Broadcasting Agency
RF	Radio Frequency
SECAM	Sequential Couleur Avec Memoire
TV	Television
UHF	Ultra High Frequency
VHF	Very High Frequency
WRC	World Radio Communication Conference

LIST OF TABLES

TABLE 1. DATA RATE VERSUS GUARD INTERVAL FOR VARIOUS MODULATION AND CODE RATES.....	18
TABLE 2. SIMULATION PARAMETERS AND VALUES USED	42

LIST OF FIGURES

FIGURE 1 DIFFERENCE BETWEEN MFN AN SFN	2
FIGURE 2 SFN WITH 10 TRANSMITTERS OPERATING ON SINGLE CHANNEL C1	10
FIGURE 3 CONCEPT OF OFDMA SIGNAL	25
FIGURE 4 OFDM SYMBOL DURATION AND FFT-WINDOW (NO GUARD INTERVAL).....	31
FIGURE 5 INTER-SYMBOL INTERFERENCE WITH A DELAYED SIGNAL (NO GUARD INTERVAL)	31
FIGURE 6 INCREASE OF THE SYMBOL DURATION BY THE GUARD INTERVAL	32
FIGURE 7 GUARD INTERVAL UTILIZATION	32
FIGURE 8 THREE POSSIBLE FFT- WINDOW POSITIONS	32
FIGURE 9 BLOCK DIAGRAM FOR DVB-T ENCODING	34
FIGURE 10 BROADCASTING OVER MFN.....	40
FIGURE 11 BROADCASTING OVER SFN	41
FIGURE 12 CHANNEL UTILIZATION (%) VS NUMBER OF TRANSMITTER WHEN SINR IS SET AT 10DB.....	44
FIGURE 13 CHANNEL UTILIZATION VS SINR WHEN THE NUMBER OF TRANSMITTER IS FIXED AT 3	45

Table of Contents

DECLARATION	i
ACKNOWLEDGMENT	ii
ABSTRACT	iii
KEY WORDS	iv
LIST OF SYMBOLS AND ACRONYMS	v
LIST OF TABLES	vi
LIST OF FIGURES	vii
CHAPTER I. INTRODUCTION	1
1.1 Background.....	1
1.2 Problem statement	3
1.3 Objectives.....	3
1.4 Scope.....	4
1.5 Outline.....	4
CHAPTER II. LITERATURE REVIEW	5
2.1 Introduction	5
2.2 Digital Broadcasting	7
2.2.1 Digital Video Broadcasting	7
2.2.2 Advantages of Digital Video Broadcasting.....	8
2.3 Single Frequency Networks.....	9
2.3.1 Definition and characteristics of SFN	9
2.4 Consideration of network structures for SFN	11
2.4.1 Transmitting sites	11
2.4.2 Transmitting antenna types and radiation patterns.....	12
2.4.3 Some factors influencing the transmitter distance	12
2.4.4 Some factors influencing the separation distance.....	13
2.4.5 Mixed MFN – SFN	13
2.5 Impact of DVB-T parameters on SFN performance	14
2.5.1 Constellation.....	14

2.5.2	Code rate.....	14
2.5.3	2K/8K FFT.....	15
2.5.4	Guard interval.....	16
2.5.5	Data rate versus guard interval.....	17
2.6	Spectrum utilization.....	19
2.7	Coverage requirements for SFN.....	19
2.7.1	Type of service and quality of coverage.....	20
2.7.2	Shape and size of coverage area	21
2.8	Limitation on SFN performance.....	22
2.8.1	Self-interference	22
2.8.2	Maximum transmitter separation distance and maximum allotment area size..	23
2.8.3	OFDM (Orthogonal Frequency Division Multiplexing)	23
2.8.4	OFDM based Single Frequency Networks	25
2.9	Implementation of the transmitter network.....	27
2.10	Self-interference.....	28
2.11	Transmitter synchronization.....	28
2.11.1	Frequency synchronization.....	28
2.11.2	Timing synchronization.....	28
2.11.3	Effect of synchronization loss	29
2.12	Multipath capability of DVB-T	30
2.12.1	Inter-symbol interference.....	30
2.12.2	Guard Interval	31
2.13	Channel Coding and Modulation.....	33
CHAPTER III. SYSTEM MODEL AND ANALYSIS.....		35
3.1	Propagation Prediction Method.....	35
3.2	Model for Terrestrial Receiver	36
3.3	Spectrum Efficiency	38
3.3.1	Channel utilization or channel efficiency	38
3.3.2	Multiuser channel utilization.....	39
3.4	Use case for channel utilization in MFN and SFN	39
3.5	Simulation Model	42
3.5.1	Simulation Parameters	42

3.5.2	Simulation Example.....	42
3.5.3	Simulation Results	43
CHAPTER IV. CONCLUSION AND RECOMMENDATION.....		46
4.1	Conclusion.....	46
4.2	Recommendation.....	47
REFERENCES		48

CHAPTER I. INTRODUCTION

1.1 Background

Broadcasting systems have the capacity to deliver an enormous amount of information to many receivers all over the world. Currently, the offered service could be an audio or a TV program which have been dominating and major source of information and entertainment for the vast majority of the population. Moreover, TV is now experiencing a renaissance with its uniqueness to supply different radio programs to an increasing mobile audience.

In broadcasting, the operator wants to supply their programs to large regions, for instance, over a city or a country. The main difference among broadcasting systems is the size of the area where the transmitted information is to be received.

To support large areas such as a country, the required infrastructure consists of a large number of transmitter sites regularly spread out. In the Multiple frequency networks (MFN) currently adopted in Rwanda, adjacent transmitters are required to use different frequencies when broadcasting the same program to avoid interference at the receiver. To reduce the cost of the infrastructure it is preferable to have large distance between adjacent transmitters. However, the distance between the transmitters cannot be too large. A transmitter can only serve a limited area, due to the spherical structure of the earth, where receivers beyond the “radio horizon” experience a severe degradation in received powers resulting in reduced reception quality.

The main limitation when providing radio communication services for a large number of programs is the shortage of radio frequency spectrum. Thus, it is essential to use the spectrum efficiently.

A fundamental approach to achieve high spectrum utilization in radio networks is to reuse the spectrum in geographically separated area. When reusing the spectrum, the transmitters must be sufficiently separated spatially such that they cannot interfere with each other. This

is the external interference aspect of the network planning, which requires a frequency reuse planning strategy [1].

The scarcity of broadcasting made the Telecom Regulator in Rwanda to license only two signal distributors for laying the necessary infrastructure for Digital TV Broadcasting, and developers of TV content use the infrastructure of one the signal distributor to air their content.

Although only 2 signal distributors were licensed, the assigned spectrum is not enough with the current MFN architecture used to cover the whole country considering also the increased number of TV content being produced requiring also more channels to be transmitted to the public.

A new type of broadcasting system has been developed, which is able to serve an arbitrary large area with the same program without reusing frequencies. This new type of network is often referred to as a Single Frequency Network (SFN). For broadcasting services such TV Broadcasting where the amount of needed bandwidth is high, this offers enormous advantages [2]. By avoiding frequency reuse, substantial improvements in bandwidth utilization are possible. Figure 1 illustrates the differences between a conventional frequency reuse network and a Single Frequency Network.

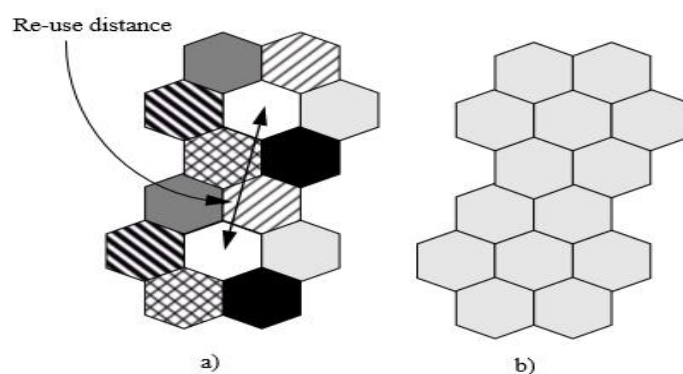


Figure 1 Difference between MFN an SFN

a) A conventional network with frequency reuse

b) A Single Frequency Network

Single Frequency Network (SFN) synchronizes transmitting stations so that they radiate identical signals using the same frequency channel.

In this thesis we will look at this new type of broadcasting concept and show how the available spectrum can be used in an effective and efficient manner to promote the availability of diverse broadcasting content and promote the TV Broadcasting industry.

1.2 Problem statement

The growing demand and technology development in mobile broadband services has recently led to a large increase in demand of more radio spectrum for mobile services. Although the spectrum demand is increasing, frequency spectrum as resource itself is not increasing which lead to its scarcity, and this further led to additional spectrum allocation for mobile services, and a big part of the allocation made to Mobile Services was previously allocated to Broadcasting services.

This allocation to Mobile Services has left fewer frequencies for television Broadcasting than the originally assigned, hence requiring more optimization and efficiency of the remained spectrum to accommodate the current need in the Broadcasting Service Sector.

1.3 Objectives

The main objective of this research project is to introduce the concept of Single Frequency Network in TV Broadcasting services, assess the benefits and advantages that it can bring in TV Broadcasting as well as to compare it with the traditional Multiple Frequency Network currently in use in Rwanda in terms of spectrum utilization efficiency.

1.4 Scope

The scope of this thesis is to study the two main schemes of resources plan and compare the results with the variant, which is the transmitter number. The study will show also how there is an improvement in spectrum efficiency for TV Broadcasting when using Single Frequency Network for the existing broadcasting sites, and for the already coordinated frequencies with neighboring countries. Proposal of new frequency requiring additional coordination process is outside the scope of this thesis.

1.5 Outline

Chapter 1 gives the introduction and statement of the thesis

Chapter 2 is the literature review. It highlights other works done in Digital TV Broadcasting, and explain the MFN and SFN concepts used in Broadcasting

Chapter 3 demonstrates the network model, performance metrics and the approach used to design our system model

Chapter 4 use findings of previous analysis to design and propose an appropriate SFN structure for TV Broadcasting in Rwanda

Chapter 5 discusses the conclusions of the thesis work and gives appropriate recommendation

CHAPTER II. LITERATURE REVIEW

2.1 Introduction

The history of broadcasting dates back to the beginning of the 20th century. In 1910, fifteen years after that Marconi and Popov independently invented the radio, and four years after the first demonstrated radio transmission using continuous wave modulation (AM) happened; DeForest made the first radio broadcast to the public. Already by 1925 there were over 500 broadcasting stations in operation in the U.S., and almost every European country had a regular broadcasting service. The first stations operated in the 330–400 m band with 50 W to 1.5 kW effective radiated power (ERP) and typically broadcast their own program. The 550-1500 kHz band was opened for AM broadcasting in North-America in 1923-1924, and within a few years it became populated by a large number of stations (some of them with up to 50 kW ERP). By the late twenties several companies provided networked broadcasting, i.e., broadcasting the same program simultaneously from many stations using different frequency channels.

Although AM audio broadcasting never disappeared, its importance as a domestic program distribution medium gradually decreased after the introduction of the FM radio, invented by Edwin Howard Armstrong in 1934. The FM transmission provided superior sound quality (high fidelity) compared to the AM system, operating in the 20–110 MHz frequency range. The first FM station started its regular operation in 1939 and 229 FM stations were licensed by 1945 in North-America alone. Another landmark was the beginning of FM stereo transmission in 1961. The beginning of video broadcasting (i.e., television) can be attributed to several major inventions such as the moving picture of the French Lumière brothers or the iconoscope of the Russian physicist Zworykin. Charles Francis Jenkins held the first television demonstration in 1923 to AT&T which made the first public television demonstration in 1927. Two years later, in 1929 the first regular TV broadcast began. An important breakthrough in the history of television was the invention of the color TV in 1940. The first authorized color TV broadcast, however, could only be started in 1951 (the U.S. Federal Communications Commission, FCC, held back earlier proposals until full compatibility with the black-and-white system was ensured).

In the developed countries, most people acquired a TV set for their home during the 60's. In the beginning and up to the 80's, broadcasting networks were dedicated, single-purpose networks. In the past few years' other services have been introduced (piggy-backed on existing radio programs) such as paging services, program-associated data services, location-dependent information distribution, teletext. During the evolution of broadcasting operators, governments and standardization bodies have placed a great emphasis on compatibility with equipment used by consumers: e.g., existing receivers were not made obsolete by the introduction of FM stereo, RDS (Radio Data System), color TV and teletext. Nowadays, digital broadcasting is being adopted in replacement to traditional analog broadcasting networks.

Analog broadcasting networks were usually based on relatively few high powered transmitters, located on highly elevated structures (hills, mountains, high buildings). In addition, to improve reception in shadowed areas a very large number of low-powered(gap-filling) were being used. The analog systems were very sensitive to interference from other analog signals, and require high co-channel protection ratios, i.e., in the order of 30 to 45 dB. The existing analog systems are also sensitive to multi-path propagation [3]. Therefore, they were being used in MFN configurations, covering adjacent areas with different RF channels. The same RF channel is re-used only in regions separated by large distances, to avoid harmful co-channel interference. Therefore, the analog radio broadcasting coverage is characterized by an intensive exploitation of the HF/VHF/UHF channels.

To alleviate the problem of spectrum saturation and to satisfy the increasing demands for better sound and picture quality, broadcasting companies started to look for the possibilities to introduce digital broadcasting around the late 80's [4]. As a result, a number of digital broadcasting systems have been designed. Two standards have been accepted in Europe, the Digital Audio Broadcasting (DAB) [5] for sound and the Digital Video Broadcasting (DVB) [6] for television. The DAB can offer CD quality services both for fixed and for mobile receivers. Based on novel source coding techniques and spectrum efficient modulation methods, the DVB can offer 8 times more programs with the same picture quality than the analog system using the same frequency block.

2.2 Digital Broadcasting

Digital Broadcasting systems are based on a wide-band multi-carrier modulation method, Orthogonal Frequency Division Multiplexing (OFDM) [7], which is capable of operating successfully in multi-path and fading environment. The multi-path generates two effects, inter-symbol interference (ISI) and frequency selective fading [8]. In OFDM the high bit rate data stream is modulated onto a large number of adjacent narrow band carriers. By ensuring that the symbol duration is sufficiently long and using a guard interval between successive symbols on each carrier, the system can absorb the inter-symbol interference created by multipath in the channel. The guard interval should have a duration which exceeds the multi-path delay spread of the channel. Since frequency selective fading impairs only a few of the carriers, the information content can be retrieved by means of powerful error correcting codes together with interleaving.

2.2.1 Digital Video Broadcasting

European and majority of African countries has adopted DVB standard which is based on MPEG-2 (Motion Pictures Experts Group) video compression. The DVB system originates from the existing 625-line, 50 Hz analog TV standard used in both PAL and SECAM systems. For High-Definition Television (HDTV) transmission, the DVB data rates are four times as demanding, since there are twice as many picture lines ($2 \times 625 = 1250$ lines), each with twice as many pixels. Therefore, if high-definition transmissions are broadcast, they cannot be received on ordinary DVB sets. In the U.S. a different digital TV standard has been proposed, the American Television Standards Committee's (ATSC's) Grand Alliance [9]. ATSC has taken off from a high-resolution platform based on computer screen standards [10].

Like DVB, ATSC standard is also based on MPEG-2 video coding. The U.S. Federal Communications Commission (FCC) has allocated 6 MHz channels for digital HDTV, whereas in Europe broadcasters have 8 MHz channels compatible with analog channels. With error correction, 38 Mbps can be delivered in each 8 MHz channel over cable and satellite transmission systems, versus the 24 Mbps in terrestrial DVB system. For mobile applications, i.e., reception in moving cars, trains, the application of stronger error correction is required, therefore the usable

data-rate is reduced to 15 Mbps. DVB networks is based on the Coded Orthogonal Frequency Division Multiplexing (COFDM) scheme [11] that makes it possible to transmit the same digital information by many transmitters simultaneously using the same frequency band. This concept is often referred as Single Frequency Network (SFN).

The specification of digital terrestrial television (DVB-T) offers a wide range of operation defined by the number of carriers, the length of the guard interval, modulation scheme and error correcting code with different code rates resulting in different level of protection. Thus, a receiver can make use of several received copies of a signal, yielding potential diversity gain. However, signals with excessive delays create self-interference [12]

2.2.2 Advantages of Digital Video Broadcasting

The operation of the digital decoder in digital terrestrial broadcasting (DTT) is guided by the data which is incorporated in the transmitted data stream. It uses service information (SI) in decoders in order to tune to and decode information being conveyed within the signal [13]. In order to differentiate one service from another, there are identifiers in decoders that are used. These characteristics give digital broadcasting more advantages over the analogue broadcasting.

Digital terrestrial television (DTT) with the use of COFDM modulation makes the signal highly immune to multipath reflections. This means that DTT can operate where an analogue signal would not tolerate interference due to multipath reflections reaching receiver at different times.

Digital broadcasting transmits many audio, audiovisual signals in one frequency channel that in analogue would require separate frequency channels thus making digital broadcasting more frequency efficient. It has also low cost transmission, constructive additional of received signals at the receiver and has diversity in content and information offered through digital broadcasting. Digital Broadcasting allows for more content providers to enter into the market since there is more slots available for carrying contents in one frequency channel for DVB-T high standard definition, one frequency channel transmits more than 8 TV programs. Therefore, with

introduction of digital television, there are increased demands for new services that were not available before.

With wide range of choices, the consumer demand is expected to increase with the digital broadcasting.

2.3 Single Frequency Networks

2.3.1 Definition and characteristics of SFN

In principle, there exist two types of terrestrial digital broadcasting networks namely the Multi-Frequency Networks (MFN) and the Single Frequency Network.

- Multi-Frequency Networks (MFN) which allow the same or different programs to be carried by individual transmitters using different frequencies; and
- Single Frequency Networks (SFN) in which distributed emission is implemented whereby the required coverage is provided through the use of multiple transmitters operating on the same frequency and carrying the same programs.

The type of network implemented depends on frequency availability, the required coverage, the number of multiplexes to be provided and may depend also on further national policies, strategies, constraints and context.

In an SFN, many receiving locations within a particular coverage area will be served by more than one transmitter, and this introduces a certain level of redundancy to signal reception and improves the service availability [16]. The field strength from a single transmitter shows statistical variations due to the presence of obstacles on the propagation path, particularly for portable and mobile reception. This field strength variation can be reduced by the presence of several transmitters located at different bearings as seen from the receiver and when one source is shadowed, others may be easily receivable [17]. This aspect of an SFN gives rise to “network gain”. An SFN can be designed to provide a more homogeneous field strength distribution throughout its coverage area than a single transmitter covering the same area.

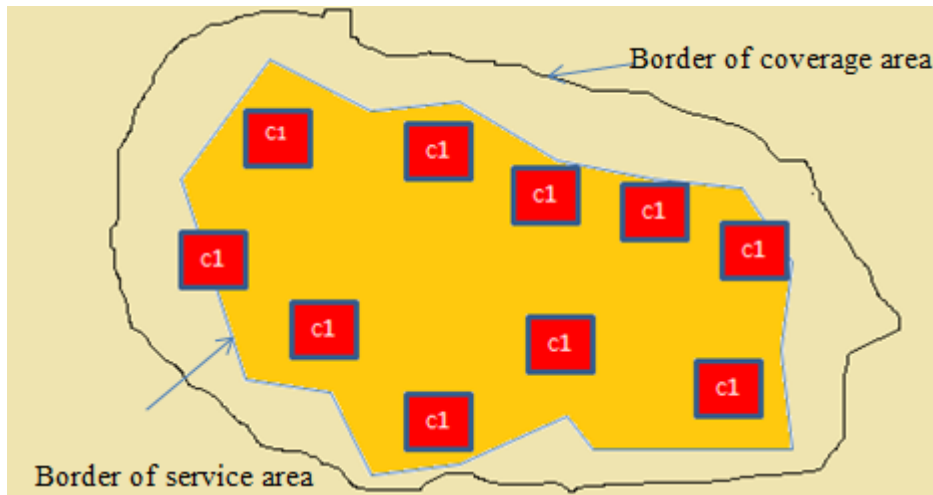


Figure 2 SFN with 10 transmitters operating on single channel C1

In a single frequency network all transmitters of a network use the same frequency and possess a common coverage area and cannot be operated independently. As shown in Figure 2, an SFN with 10 transmitters operating on single channel C1 is given and it shows the service area as well as the common coverage area of the transmitters.

When operating in an SFN, the signals transmitted from individual transmitters should be:

- synchronous in time (or with a precisely controlled delay);
- nominally coherent in frequency (within a few Hz);
- must have identical multiplex content.

The SFN approach allows for a more homogeneous field strength distribution than the MFN approach, which is particularly important for portable and mobile reception [18]. In the case of mobile reception, the SFN approach does not require a frequency handover in the receiver when moving within the coverage area. The use of SFN is facilitated by the multi-carrier OFDM modulation technique which enables the reception (and constructive summation) of more than one useful RF signal. Compared with a conventional MFN, an SFN allows significant improvements in spectrum utilization.

2.4 Consideration of network structures for SFN

2.4.1 Transmitting sites

Digital terrestrial broadcasting deployment can use existing sites for previous analogue broadcasting sites, new sites, or alternative network architectures. These parameters thus affect the choice of the selected digital terrestrial broadcasting variant and the frequency requirements. The number of transmitter sites deployed and the separation distances will vary a lot from country to country and will depend on the system variant, the reception mode (fixed, portable or mobile), the country size and boundary situations. For digital terrestrial broadcasting, the separation distance between transmitter sites may vary between 30 and 50 km in the most populated areas and between 75 and 125 km in the less populated areas.

In an SFN using appropriate digital terrestrial broadcasting standards, the separation distance between transmitters influences the choice of the guard interval, which in turn limits the size of the network [19]. The separation distance and the effective height influence the effective radiated power (e.r.p). The use of “dense networks”, a network of closely situated, low to medium power stations, can offer some advantages over networks based on high power transmitters separated by large distances (60 to some 100 Kms).

Particularly in the case of regional SFN, but also for national SFN, it is possible to consider various forms of dense networks having significantly lower e.r.p. than that required by a single transmitter serving the same area. For digital terrestrial broadcasting, the concept of “distributed emission” can provide the needed field strength over the entire service area by a number of low power, synchronized SFN transmitters, located on a more-or-less regular lattice, or to use on-channel repeaters receiving their signal off-air from the main transmitter, to improve the coverage of the main transmitter [20]. In the latter case, the re-transmitters need not be synchronized in time, and no parallel transmission infrastructure is needed to bring the signal to these on-channel repeaters.

Furthermore, local high density SFN could be used to supplement large SFN in areas where the coverage would otherwise be inadequate, due to the terrain topography. Finally, they offer a reduction of the impact of co-channel interference at the border of the service area, by introducing a sharper field strength roll-off. This can be further improved by a suitable exploitation of the transmitting antenna directivity.

For example, it is possible to envisage transmitter topologies in which the central part of the service area is covered by a large SFN (with high power transmitters separated by large distances), but near the border a dense transmitter network is installed (with low e.r.p., and with low-height and directive antennas). This allows the e.r.p. to be “tailored” according to the service area contour, reducing the interference to adjacent areas and keeping high the service availability inside the wanted area. This technique can be useful also on the borders of national SFN.

2.4.2 Transmitting antenna types and radiation patterns

Transmitting antennas will have either omni-directional or directional pattern. For stations located along or close to either country or sea borders directional antennas should preferably be used to reduce interference outside service areas, thus reducing the separation distance for the frequencies in question, and to protect coverage areas of existing services [21]. This is especially true for high and medium power stations and will in general result in a more efficient use of the frequency spectrum.

Beam-tilt, applied for antennas with effective height more than 100 m, is an efficient tool to target the radiated power of high power stations to the outer part of the coverage area and, at the same time, to reduce the interference potential at large distances and to the aeronautical service.

2.4.3 Some factors influencing the transmitter distance

There are several factors that influence the transmitter distance, for example radiated power, antenna height, reception mode, system variant and propagation path. It must be noted that these

may be different for different reference networks. In SFN networks, the distance between adjacent transmitters is limited by the length of the guard interval [22].

2.4.4 Some factors influencing the separation distance

The separation distance between two co-channel service areas is the minimum distance needed in order to avoid undue interference to either of the two service areas. The separation distance has a significant influence on the number of frequency blocks or channels needed to establish coverage of a larger area containing several countries or regions, each having its own programs transmitted in one frequency block or channel [23].

Coverage areas served by transmitters located along the periphery and using directive antennas pointing inwards (that is, in a closed network) will result in shorter separation distances compared to equivalent coverage achieved by the use of non-directional antennas (that is, in an open network).

2.4.5 Mixed MFN – SFN

The SFN approach can also be mixed with the MFN concept. This may be encountered in the following cases:

Within an MFN using high power main stations, if one such station does not provide complete coverage, lower power relay stations (gap-fillers or repeaters) may complete the coverage using the same frequency as the one used by main station [24]. This configuration can be also called hybrid MFN - SFN.

Another case may consist of using an MFN structure for transmitting a national multiplex and an SFN structure for transmitting a regional multiplex.

2.5 Impact of DVB-T parameters on SFN performance

2.5.1 Constellation

The DVB-T specification allows for three different phase/amplitude constellations, QPSK (4-QAM), 16-QAM and 64-QAM, in order to meet the different requirements in terms of spectral efficiency and the reliability of the broadcast service [25].

The choice of constellation determines the number of bits that are carried at a time on each sub-carrier; 2 bits for QPSK, 4 bits for 16-QAM or 6 bits for 64-QAM may be carried. Moreover, the modulation has an important impact on the performance in a SFN as the choice of constellation also determines noise tolerance, with QPSK being around 4 to 5 times more tolerant than 64-QAM meaning QPSK provides a low data capacity but it does provide a very rugged service. Networks using QPSK may be of particular value in urban areas for services to pedestrians and vehicles.

16-QAM provides a moderate capacity and, therefore, this variant may be of interest for providing reasonably rugged services to medium or densely populated areas while 64-QAM variant has a high data capacity but does not provide rugged services and is particularly sensitive to self-interference effects in large area SFN.

2.5.2 Code rate

Different code rates can be used to trade bit rate versus ruggedness, e.g. the signal strength required and interference protection required [26]. The code rate of $1/2$ has the highest redundancy and in doing so the highest transmission safety albeit at the cost of data throughput. This mode should only be applied to channels that have a high degree of interference.

The variants using code rates higher than $3/4$ offer additional capacity but may be not worthwhile as the system becomes less rugged. For code rates $5/6$ and $7/8$ the implementation margins may also be higher than expected making those variants even less attractive. The code rate of $7/8$ has

the lowest redundancy but the highest throughput. As such, it should only be used for channels with low levels of interference.

In the case of mobile reception under SFN environment, since the speed of the mobile receiving terminal relative to different transmitters is often different, this will result in strong Doppler effects, which have to be dealt with by channel estimation and error correction system. A lower rate of convolutional coding like 1/2 is thus recommended for mobile implementation.

2.5.3 2K/8K FFT

The DVB-T standard defines two FFT modes (2K and 8K) each using different numbers of Sub-carriers (2048 and 8192) to constitute the OFDM signal. This means different symbol Times $T_u = 896 \mu s$ and $T_u = 224 \mu s$.

The 8K FFT systems provide a higher degree of protection against inter-symbol interference caused by multipath propagation. The use of a higher number of carriers within the same bandwidth increases the symbol period (in order to preserve orthogonality) and therefore the same proportion of guard interval gives a greater protection [27]. In the 2K FFT systems, signal delays that exceed the guard interval are very much more conspicuous due to the considerably shorter usable symbol time of $224 \mu s$. Thus, the 2K FFT systems are not meant for large area SFN.

However, the 8K FFT mode presents a higher complexity and a higher sensitivity to tuner phase noise and may be less suitable for mobile reception. The DVB-T 2K FFT systems can withstand moving echoes up to several hundred Hz. Therefore, this mode is superior for mobile applications. The working frequency of each SFN transmitter should be accurately managed and monitored. For COFDM SFN operation, the stability and the accuracy of the transmitter's working frequency shall ensure that each sub-carrier has the same absolute frequency position in the RF channel.

2.5.4 Guard interval

In an SFN each transmitter is required to radiate the same OFDM symbol at the same time. This comes from the fact that echoes (natural or artificially generated by co-channel transmitters) shall be confined in the guard interval period. The OFDM receiver has to setup a time-window during which it samples the on-air OFDM signal. The objective is to synchronize this time-window with the useful period of the OFDM symbol. Accordingly, it will ignore the signal during the guard interval period where the receiver signal is made of a mixture of two or more OFDM symbols [28].

If the transmitters deliver the same OFDM symbol at the same instant, or with a sufficiently small time delay, the differential propagation path delay to the OFDM receiver will remain inside the guard interval period. Accordingly, the sum of the received signals will be constructive because they constitute the same OFDM symbol (no inter-symbol interference).

The DVB-T specification offers a selection of system guard intervals, i.e., 1/32, 1/16, 1/8 or 1/4 times the duration of the useful symbol duration. For 8K(2K) mode this represents a permitted guard interval duration of 28(7) μ s, 56(14) μ s, 112(28) μ s and 224(56) μ s, respectively.

The selection of the appropriate guard interval parameter for digital terrestrial television affords resilience against delayed, interference-causing signals in television reception. Moreover, the guard interval value chosen to operate an SFN has a major implication on the topology of the SFN network: as the guard interval duration governs the maximum echoes delay admissible by the system, it governs accordingly the maximum possible distance between co-channel transmitters (producing active echoes).

Some modes allow setting up large SFN networks having a great distance between high and medium power transmitter's sites. Some others allow smaller service areas with a greater density of low power transmitters. The guard interval selection should be based on the distance between the transmitters [9].

The spacing between adjacent transmitters in an SFN should not be significantly greater than the propagation time permitted in the guard interval:

In a 2K-FFT system the guard interval values are: 7 μ s, 14 μ s, 28 μ s, 56 μ s. These values translated into distance give respectively: 2.1 km, 4.2 km, 8.4 km, and 16.8 km.

In an 8K-FFT system the guard interval values are: 28 μ s, 56 μ s, 112 μ s, 224 μ s. These values translated into distance give: 8.4 km, 16.8 km, 33.6 km, and 67.2 km.

Studies on the maximum distance between transmitters in theoretical SFN for DVB-T and TDAB systems have shown that together with the guard interval the maximum inter-transmitter distance is influenced by the system variant required and the effective radiated power of the transmitters in the network.

2.5.5 Data rate versus guard interval

Because the guard interval reduces the amount of time available for data transmission, its setting has an effect on the DVB-T net deliverable bit rate. Lengthening the guard interval decreases the bit rate. The guard interval 1/32, 1/16, 1/8, 1/4 produce respectively a loss of 3.1%, 6.2%, 12.5% and 25% in the transmitted bit rate. Table 1 indicates the net bit rate in Mbits/s for various modulations, combinations of guard interval settings and error protection code rates. The data are given for the bandwidth of 8 MHz.

Table 1 Data rate versus guard interval for various modulation and code rates

Modulation	Code rate	Guard Interval			
		1/4	1/8	1/16	1/32
QPSK	1/2	4.98	5.53	5.85	6.03
	2/3	6.64	7.37	7.81	8.04
	3/4	7.46	8.29	8.78	9.05
	5/6	8.29	9.22	9.76	10.05
	7/8	8.71	9.68	10.25	10.56
16-QAM	1/2	9.95	11.06	11.71	12.06
	2/3	13.27	14.75	15.61	16.09
	3/4	14.93	16.59	17.56	18.10
	5/6	16.59	18.43	19.52	20.11
	7/8	17.42	19.35	20.49	21.11
64-QAM	1/2	14.93	16.59	17.56	18.10
	2/3	19.91	22.12	23.42	24.13
	3/4	22.39	24.88	26.35	27.14
	5/6	24.88	27.65	29.35	30.16
	7/8	26.13	29.03	30.74	31.67

To maximize the net bit rate, the guard interval is often chosen as small as possible, reducing accordingly the maximum echoes delay but also the maximum distance between transmitters, thus practically disallowing in many cases to operate 2K-SFN.

2.6 Spectrum utilization

SFN configuration allows a very large flexibility in the use of spectrum. A network can be initially designed to provide coverage to fixed roof-level antennas, but can be developed later, without the need for additional frequencies, to provide mobile or portable services by the addition of supplementary frequency and time synchronized stations, all carrying the same data stream.

This can be a way of spreading the cost of introducing a new digital network over a period of time. For example: if the initial investment required to provide a network which delivers indoor coverage to the whole target area is too high, The Signal Distributor could choose to implement a network with a variety of reception modes starting par example with coverage in general to fixed roof-level antennas with a priority given to portable reception in some towns inside the target area. The ‘fixed’ coverage network can then be developed to provide further indoor coverage over a period of time. However, this facility can be conceived only in a frame of a frequency planning studied in advance.

Another flexibility that the SFN brings is the freedom for a broadcasting operator to implement new stations to improve coverage within an existing network, without having to request additional spectrum.

2.7 Coverage requirements for SFN

Coverage is a term used to describe what portion of an area (for example, this could be a country or region) where a particular broadcasting service is predicted to be receivable. Coverage is usually expressed as the percentage of location or population covered in a given area [30]. The prediction of coverage is normally carried out using a standardized set of requirements and assumptions (as agreed at an international level normally through the ITU). Coverage predictions

are generated to ensure that a new service can operate at maximum power whilst minimizing any interference to users receiving existing services.

Coverage requirements for SFN can be considered as follows:

- The length and breadth of the coverage area in terms of the physical size. The coverage area can also be approximated conveniently as circular, in which case a radius is usually quoted.
- The height at which the coverage is required. For fixed aerial reception, the standard height is 10 m. For portable reception, the height is usually set at 1.5 m above the floor level, which applies to the ground, the first or a higher floor depending on what is the requirement. For mobile reception, the height is usually set at 1.5 m above ground level.

As a country's coverage requirements may change as technology advances or consumer demand increases, a further dimension that may need to be considered is "time" (i.e. coverage requirements may change over time, so some element of "future-proofing" may need to be built in). The addition of transmitters at a later stage can enable the coverage to be completed if this is subsequently found to be necessary [29].

2.7.1 Type of service and quality of coverage

It is very crucial that an administration decide at an early stage of the planning process how much of the territory is to be covered, for a given type and number of services which may have different quality requirements. The type of service means fixed, portable or mobile reception, the quality of coverage, often also called "location probability", is usually described as "good" or "acceptable". "Good" is normally understood as a location probability of 95% while "acceptable" is taken to be 70% in a test area, i.e. where at least 95% or 70% of the locations are predicted to be served.

The service type and quality does not need to be homogeneous throughout a territory.

Heterogeneous coverage can be planned so that portable reception is available in a densely populated urban center with a location probability of 95%, which decreases to say 70% (fixed reception) as one moves outwards to more sparsely populated rural areas at the periphery.

2.7.2 Shape and size of coverage area

In an SFN, all transmitters in the network use the same channel. Thus they possess a common coverage area and cannot operate independently. They require a high degree of synchronization; the emitted signal from different transmitters must be identical in content, signal emissions must take place at the same time (or with precisely controlled delays) and the RF carriers must comply with stringent frequency precision requirements.

Spectrum usage, network design and the shape and size of coverage are all inter-related. For example, a SFN using one frequency designed to achieve nationwide coverage will probably use a different network structure than a network chain that serves the same nationwide area by means of several SFN using several frequencies on a regional basis.

SFN coverage, in general, could be considered in three different sizes:

- Firstly, a national SFN, where all the stations use the same channel. Complete implementation of such a network using the same frequency depends on the coordination of the frequency being agreed everywhere on the country borders, which may be difficult. A national SFN must broadcast the same program everywhere. In a synchronized SFN, the coverage provided by each transmitter is limited in practice to 60 - 70 km radius, due to the guard interval limiting the distance between transmitters. Coverage areas may need to be decoupled, for example by sufficient distance separation or shielded from each other by mountains, to minimize self-interference. Thus, national SFN providing complete coverage of a country may be generally difficult because of self-interference effects, depending on the chosen system variant.
- Secondly, a regional SFN, where all the stations in a region use the same channel, but neighboring regional SFN use different channels. So, for example, four channels could be used

in total to cover the country with a regional service, on a “map coloring” basis. Sites associated with different regions broadcast different programs some of the time or all of time.

- Thirdly, a sub-regional SFN configuration, where the main station and its relays use the same channel, but the neighboring main station within the same region uses a different channel. For example, four channels could be used to cover the country with sub-regional SFN on a “map coloring” basis. Sites associated with different sub regions broadcast different programs some of the time or all of time. SFN based on the main transmitter infrastructure of existing analogue networks are likely to be best suited for fixed roof-level reception. For networks that are intended for portable or mobile reception a higher transmitter density is desirable in many cases.

One significant advantage of the SFN approach is the possibility to develop dense networks. These employ a different network topology, with a large number of low power stations (for instance < 100 W effective radiated power, < 75 m effective transmitting antenna height) distributed over the service area (potentially with a main transmitter at the centre) providing a more homogeneous field strength distribution. This type of network structure is chosen to provide a high level of field strength as is in particular necessary for portable and mobile reception. Careful consideration of site height, transmitter spacing and guard interval is essential to ensure that no self-interference effects are experienced.

2.8 Limitation on SFN performance

2.8.1 Self-interference

The power of all signals in an SFN received within the time width of the guard interval is treated as useful, and contributes to the total available signal power. Outside the guard interval, only a part of the echo power is associated with the same OFDM symbol as the primary signal, and therefore contributes positively to the total useful signal power. The other part of the echo power is associated with the previous or subsequent OFDM symbol and produces inter-symbol interference. Therefore, as the signal delay is progressively increased beyond the guard interval, the useful contribution decreases and the inter-symbol interference increases.

2.8.2 Maximum transmitter separation distance and maximum allotment area size

This gives rise to two restrictions imposed on SFN. Firstly, for a given receiving location, the main contributing signals in an SFN come from the nearby transmitters. In order to keep these contributions constructive, the time delay between them must not exceed the guard interval remarkably, which means that neighboring transmitters have to keep a certain upper limit for the distance between them.

Secondly, even if the maximum separation distance for neighboring transmitters is kept, more distant transmitters in the network may contribute destructively in such a way that a maximum extension of the SFN service area must not be exceeded in order to keep the number of relevant self-interfering transmitters small.

The significance of self-interference, the resulting maximum separation distance between neighboring transmitters and whether there is an overall maximum extension of the SFN service area depends on the chosen guard interval, the sensitivity of the system with regard to self-interference, indicated by the relevant C/N value, and the density of the transmitters in the network.

In a large SFN, it may be difficult to plan the network so that signals from transmitters a long distance away from the receiver are always of an insignificant level compared to those from nearby transmitters.

2.8.3 OFDM (Orthogonal Frequency Division Multiplexing)

OFDM is especial case of Multi -carrier transmission, where a single data stream is transmitted over a number of lower rate sub-carrier. It is worth mention here that OFDM can be seen as either a modulation technique or a Multiplexing technique. One of the main reasons to use OFDM is to increase the robustness against frequency selective fading or narrowband interference. In single carrier system, a single fade or interference can cause the entire link to fail, but in Multi -carrier system, only a small percentage of the sub -carriers will be affected. Error correction coding can then be used to correct for the few erroneous sub -carriers.

The concept of using parallel data transmission and frequency division Multiplexing was published in the mid-1960s [31]. In parallel data system, the total signal frequency band is divided into N non-overlapping frequency subchannels. Each sub-channel is modulated with a separate symbol and then the N sub-channels are frequency Multiplexed. It seems good to avoid spectral overlap of channels to eliminate inter-channel interference.

OFDM is similar to FDMA in that the multiple user access is achieved by subdividing the available bandwidth into multiple channels, which are then allocated to users. However, OFDM uses the spectrum much more efficiently by spacing channels much closer together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the closely spaced carriers. In FDMA each user is typically allocated a single channel, which is used to transmit all the user information. The orthogonality of the carriers means that each carrier has an integer number of cycles over a symbol period. Due to this, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, allowing them to be spaced as close as theoretically possible. This overcomes the problem of overhead carrier spacing required in FDMA.

Each carrier in an OFDM signal has a very narrow bandwidth (i.e. 1 kHz), thus the resulting symbol rate is low. This will give the signal a high tolerance to multipath delay spread, because the delay spread must be very long to cause significant inter-symbol interference. In the mobile radio environment, signals are usually impaired by fading and multipath delay spread phenomenon. In such channel, severe fading of the signal amplitude and Inter-symbol interference lead to unacceptable degradation of the system error performance. It is expected that OFDM is capable of providing very high data rate with strong robustness of multipath delay spread, which make that Inter-symbol interference (ISI) is no longer a problem.

Figure 1.5 illustrates the difference between the conventional non-overlapping Multi-carrier technique and the overlapping Multi-carrier modulation technique. As can be seen from the figure 3 by using the overlapping Multi-carrier modulation technique, we save almost 50% of bandwidth. In the 1980s, OFDM was studied for high speed modems, digital mobile

communications, and high density recording. In 1990s, OFDM was exploited for wideband data communications over mobile radio FM channels, high bit rate digital subscriber lines (HDSL 1.6Mbps), asymmetric digital subscriber lines (ADSL up to 6Mbps), very high speed digital subscriber lines (VDSL 100Mbps), digital audio broadcasting (DAB), and high definition television (HDTV) terrestrial broadcasting.

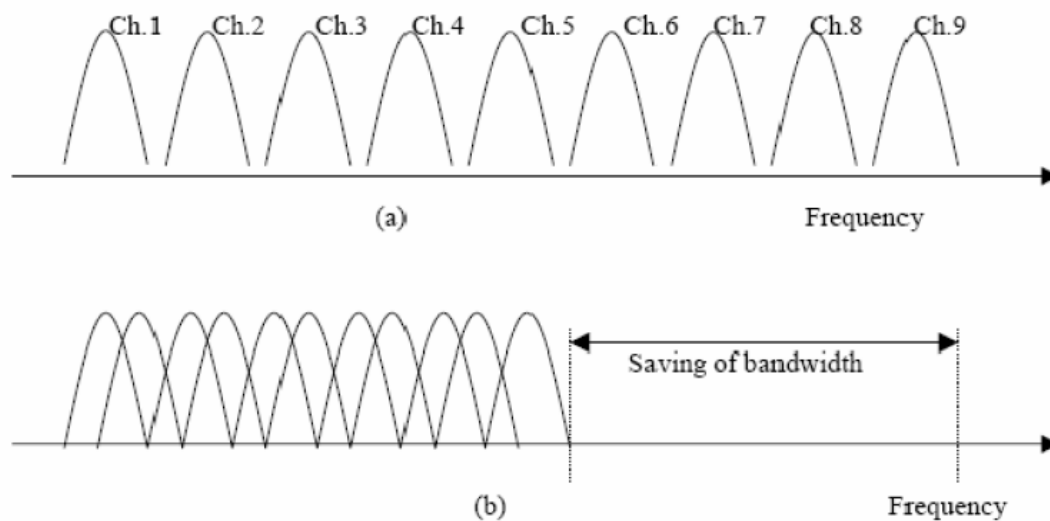


Figure 3 Concept of OFDMA Signal

(a) Conventional Multi Carrier Technique (b) Orthogonal Multi Carrier Technique

2.8.4 OFDM based Single Frequency Networks

The capability of OFDM to overcome multi-path interference allows distributing a program over all transmitters in a radio network using the same frequency block. In such a Single Frequency Network (SFN), the useful signal at a receiver is the superposition of all signals coming from those transmitters that distribute the required program. In such SFNs large diversity gain (or network gain) is obtained yielding better coverage and frequency economy than in analog broadcasting networks [32].

The main advantages of implementing SFN compared to the conventional multi frequency network are the following:

- High spectrum efficiency compared to the MFN approach. Spectrum efficiency is very important in a scarce spectrum environment both at the introductory phase when the spectrum is occupied by analog services and also in long term when a large number of offered programs make the broadcasting services more attractive for customers.
- In SFN the received signal is a superposition of signals coming from several transmitters. The variation of the total field strength is lower, since one of the transmitters is shadowed, whereas the others are still receivable. This results in a higher location probability. This phenomenon is usually referred network gain or diversity gain.
- As a result of the network gain, SFN can operate at lower power and the field strength distribution over the total service area is more homogeneous compared to MFNs.
- SFN allows the easy setup of gap-filling transmitters where bad reception quality is observed, i.e., without using extra frequencies.
- Increased robustness is ensured using dense SFNs in which the failure of a single transmitter does not result in coverage outage for the whole network.

However, the following few disadvantages of SFNs subsist and shall be dealt with care for a successful SFN implementation

- Time synchronization among the transmitters of the SFN is necessary: the signal emissions must take place at the same time, or with precisely controlled delays from each transmitter.
- Precise frequency synchronization is needed both at the transmitter and at the receiver, because errors generate frequency orthogonality losses for the received signals.

In a SFN multiple copies of the signals arrive at the receiver antenna with different delays. The time dispersion is caused by two main mechanisms. The “natural” dispersion is caused by wave components reflected by obstacles in the vicinity of the receiver and the “artificial” dispersion derives from the reception of signals from several transmitters placed at different distances from the receiver. The delay of the “natural echoes” is usually limited to 20–30 μ s, corresponding to a difference in the propagation path of up to 10 km. Since the symbol duration is very long compared to the “natural” dispersion, the effects of reflection in the vicinity of the receiver can be neglected. Thus, the inter-symbol interference is caused mainly by the “artificial” delay spread.

In OFDM systems the extreme delay spread is controlled by using a longer transmitted symbol than the actual interval observed by the receiver. If the delay spread of the signal is smaller than the guard interval, no inter-symbol interference occurs and the signal contributes totally to the wanted signal. Signals of transmitters located far away from the receiver can cause inter-symbol interference and turn into interfering signal because of the excessive delay. Those signals arriving in between contribute partially both to the wanted and to the interfering signal. This phenomenon is called self-interference. Therefore, in SFNs not only noise but also delayed signals outside the guard interval have an important impact on the achievable coverage.

2.9 Implementation of the transmitter network

The implementation of any particular SFN is unlikely to be identical to any other. Factors such as terrain, population distribution and coverage requirements will vary and have a significant impact on network design and implementation. Planners should use their own knowledge and judgement on which parts are appropriate to their needs. A plan for a new SFN will either be based on an existing allotment in a Plan (for example, the GE06 Plan), or represent a new requirement which will require coordination.

2.10 Self-interference

In an SFN it is possible for signals to arrive from distant transmitters outside the guard interval. Signals outside the guard interval can cause self-interference in the network. Although it may only occur for short percentages of time it does need to be considered. Self-interference can be reduced by either advancing or delaying the launch of the service from some transmitters in relation to a fixed reference. Signals exceeding guard interval may arrive from distant SFN sites by the abnormal propagation. Possible solutions for such cases could include assigning the other channels than the SFN, or building complementary transmitting sites.

2.11 Transmitter synchronization

In order for an SFN to operate correctly all of the transmitters in the network need to be synchronized with one another. This requirement is true in both the frequency and time domains.

2.11.1 Frequency synchronization

The frequency accuracy of the digital transmitter will normally be very stable. However, in order to minimize any drift all transmitters should be locked to a reference source, for instance with GPS.

2.11.2 Timing synchronization

In order to reduce intra network interference it is possible to adjust the time at which a specific signal frame is launched from each transmitter of the network, the relative transmitter timing. Optimizing this delay allows the signals from both near and distant transmitters to arrive at the receiver within the guard interval, thus being constructive rather than destructive. The relative transmitter timing can be adjusted to be either in advance of or after the reference point. However, in all cases the time of signal transmission at each transmitter of the network needs to be referenced to a time reference.

Distribution of the service content also needs to be considered so that the same data frame is transmitted during the same time period, either with or without any required delay. Over a large, e.g. national, network the arrival of the content information to transmitters may vary significantly. One option is to feed the content signal directly to the network sites using satellite distribution. In a small SFN, i.e. one that is not larger in diameter than the signal can travel in the guard interval, it should not be necessary to consider this element of network planning.

When initially designing the network configuration the planner needs to predict both the wanted coverage and the interference potential of each transmitter. These predictions should be carried out at 50% time for the wanted service and 1% time for the interferer. With the relative timing delay set to zero the coverage of the whole network can be derived. At which point the overall interference caused by each transmitter into the SFN can then be calculated. In general, it will be the highest power assignments which will cause the most interference and it is reasonable to focus on them initially. However, adjusting the timing of sites with lower e.r.p.s. can lead to significant coverage gains around the periphery of their service areas. Transmitter that can interfere with should ideally be identified during the planning of the network. Once the destructive transmitters have been identified the network timings can be adjusted and the interference recalculated. It should be noted that the transmitter causing the greatest interference may not be the one to adjust since a change may simply cause a problem in a different part of the network. It may be a better strategy to retard the smaller site(s) so that their signals are received within the guard interval of the distant high power site. Consideration should also be given to how receiver synchronization is implemented in the prediction models.

2.11.3 Effect of synchronization loss

If a transmitter is allowed to drift out of synchronization with the rest of the network, it will become a source of interference to the coverage of the rest of the network. This will be noticeable as an area of lost coverage toward the periphery of the un-synchronized transmitter's coverage area, a "mush" zone. As the transmitter drifts further out of synchronization with the rest of the

network the mush zone will become progressively larger. It should be noted that reception close to the drifting transmitter, where received field strengths are high, are unlikely to be affected.

2.12 Multipath capability of DVB-T

In OFDM the information is carried via a large number of individual carriers in a frequency multiplex. Each carrier transports only a relatively small amount of information and high data capacities are achieved by using a large number of carriers within a frequency multiplex. The individual carriers are modulated by means of phase shift and amplitude modulation techniques. Each carrier has a fixed phase and amplitude for a certain time duration during which a small portion of the information is carried. This unit of data is called a symbol; the time it lasts is called the symbol duration. After that time period the modulation is changed and the next symbol carries the next portion of information. A DVB-T receiver has to cope with the adverse conditions of the broadcast transmission channel. In general, signals arriving at a receiver by different paths show different time delays which result in inter-symbol interference (ISI), a degradation in reception. An OFDM system with a multipath capability allows for the constructive combination of such signals. This is achieved by inserting a guard interval, a cyclic prolongation of the useful symbol duration of the signal. The FFT-window, i.e. the time period for the OFDM demodulation, is then positioned in such a way that a minimum of inter-symbol interference occurs.

2.12.1 Inter-symbol interference

In order to demodulate the signal – and looking at only one carrier – the receiver has to evaluate the symbol during the symbol duration. Three consecutive symbols in time, denoted by $n-1$, n and $n+1$, and the setting of the FFT-window such that symbol n is evaluated by the receiver, are shown in Figure 2. No guard interval is used in this example, and the FFT-window has the same duration as the symbol.

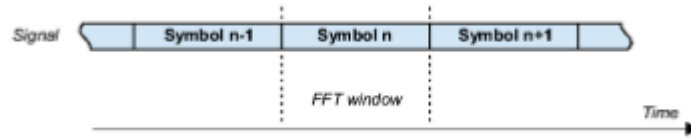


Figure 4 OFDM Symbol duration and FFT-window (no guard interval)

In an environment where several useful signals—either from multipath echoes or from other transmitters in an SFN—are available to the receiver, things become more complex. Usually, the signals arrive at different times at the receiver which, in the absence of a guard interval, makes correct synchronization to all of the signals impossible. Such a situation with two signals as an example is depicted in Figure 3. Synchronization to symbol n of signal 1 leads to an overlap of the FFT-window with the preceding symbol $n-1$ of the delayed signal 2. Since this symbol $n-1$ carries different information from symbol n , the overlap acts as interference to the evaluation of symbol n . The degradation of the reception caused by this mechanism is called inter-symbol interference (ISI).

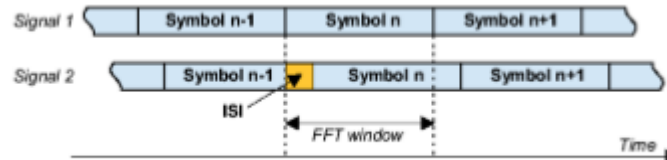


Figure 5 Inter-symbol interference with a delayed signal (no guard interval)

2.12.2 Guard Interval

In order to overcome the inter-symbol interference problem in DVB-T, DVB-T2 and T-DAB, part of the symbol is copied from the beginning of the symbol to the end, increasing its duration by a certain amount of time called the guard interval. This cyclic prolongation of the original symbol is shown in Figure 4. The guard interval is denoted by Δ .

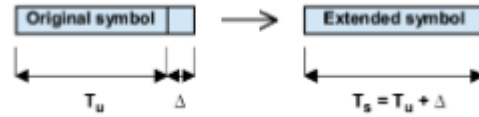


Figure 6 Increase of the symbol duration by the guard interval

The new increased symbol duration is denoted by T_s and the original symbol duration is often called useful symbol duration T_u . The duration of the FFT-window during which the symbol is evaluated is kept at the original value T_u . The orthogonal relationship is kept with the original symbol duration T_u , not the extended T_s . The improvement that is achieved by the insertion of the guard interval can be seen from Fig.5 with two signals as an example. The guard interval now allows for the FFT-window to be positioned so that there is no overlap with a preceding or subsequent symbol, thus avoiding ISI.

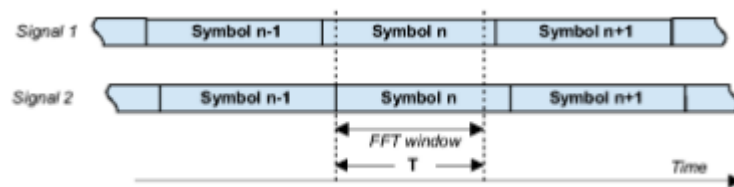


Figure 7 Guard Interval Utilization

The fact that the duration of the FFT-window is now smaller than the symbol duration allows for a variety of different possible FFT-window positions for the evaluation of a symbol. This is indicated in Fig. 6 for the simple case of synchronization to a single signal. Three possible FFT-window positions are indicated as examples. Here, all positions are equivalent with regard to evaluation of the symbol because all the FFT-window positions shown include samples from only one symbol.

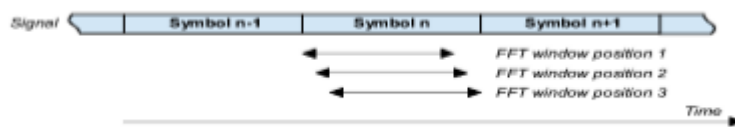


Figure 8 Three possible FFT- window positions

The insertion of the guard interval reduces the data capacity because not all of the symbol duration T_s is used for "useful" data. In a multipath or SFN environment, where many potentially useful signals are available to the receiver, the choice of the FFT-window position becomes more complex. All signals with time delays that cannot be absorbed by the guard interval in the way described above introduce a degradation of reception, similar to that shown in Fig 2. Any part of each of these received signals that falls outside the guard interval has an interfering characteristic. OFDM, due to its multicarrier nature, exhibits relatively long symbols. This long symbol period already provides a certain degree of protection against inter-symbol interference caused by multipath propagation.

As the proportion of the symbol used to make the guard interval is increased, the transmission capacity decreases. However, if a system with a greater number of carriers were used, the symbol period would increase and therefore the same proportion of guard interval would give a greater protection in terms of absolute time. However, increasing the number of carriers has also some drawbacks: – higher complexity (FFT performed on a higher number of samples and more memory) – higher sensitivity to tuner phase noise.

2.13 Channel Coding and Modulation

The first step in the DVB-T, before transmitting the base band signal, is to undergo channel coding and modulation. Errors occur as the result of noise and other disturbance in the transmission path. These errors can be corrected with the help of Forward Error Correction (FEC) in the receivers. Figure 7 illustrates the complete block diagram for DVB-T encoding.

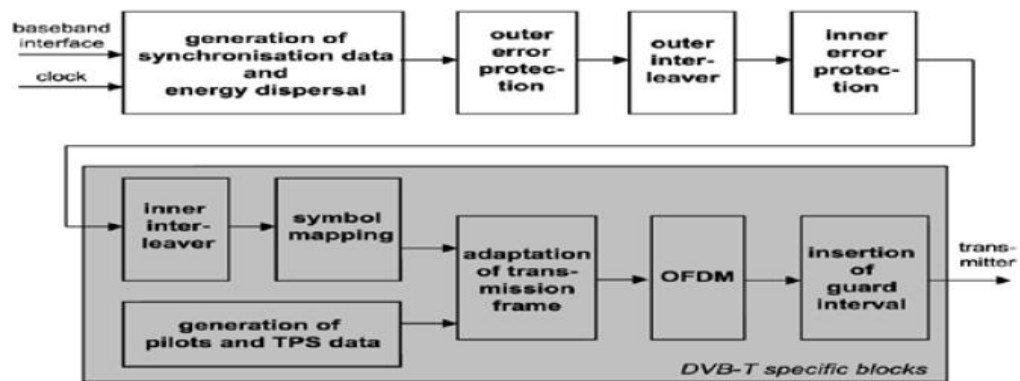


Figure 9 Block Diagram for DVB-T encoding

CHAPTER III. SYSTEM MODEL AND ANALYSIS

3.1 Propagation Prediction Method

Consider an SFN consisting of N number of transmitters. First of all, the contribution of the set of transmitters at each receiving location must be estimated according to a suitable propagation prediction method. Two prediction methods for point-to-area terrestrial services in the UHF band provided by ITU-R P.1546, P.1812, as well as the propagation by diffraction models of the ITU-R P.526 have been considered [33]-[34]. According to the principles of each ITU propagation model, its choice and application can lead to significant differences on the final coverage achieved. For instance, the ITU-R P.526 introduces a thorough analysis of the orography, evaluating the diffraction assuming several models depending on the number, type of obstacle and path geometry as well. On the contrary, the ITU-R P.1546 is based essentially on statistical analysis of experimental data, makes a light study of terrain clearance and clutter obstructions and is not suitable for hilly regions in which relevant obstacles are close to either transmitter or receiver sides, or far away from the receiver (more than 16 km).

Furthermore, for flat-terrain scenarios this ITU propagation model introduces significant electric field prediction differences with any other model when the effective height of the transmitter antenna is lower than 10 m. Finally, the ITU-R P.1812 complements and overcomes some limitations of the P.1546, introducing a path-specific propagation method. In order to apply such prediction methods to any path profile, the SRTM nearly 90 m resolution digital elevation models (DEM) provided by the NASA have been used and appropriately processed by a geographic information system (GIS) based application. In addition, a 1:25000 national topographic data base with details of the buildings has also been considered to take into account the effect of the populated areas. Basically, this block returns the signal strength (P_n , $1 \leq n \leq N$) and propagation delay (δ_n , $1 \leq n \leq N$) associated with each transmitter ($1 \leq n \leq N$) at each receiver point ($1 \leq r \leq R$) inside the geographical area under analysis.

3.2 Model for Terrestrial Receiver

Transmission systems, together with their associated network topology are often characterized by the minimum required number of frequency channels to cover a large area, or layer. This is called the frequency re-use figure. This number of channels has to be made available in order to cover the whole layer even if not all channels are used in all locations.

The SFN transmission can be considered as a severe form of multipath propagation, so all the signals arriving at each receiving location from each transmitter must be properly treated in the OFDM receivers to maintain the spectrum efficiency. Basically, the receiver block synchronizes and combines all these echoes to obtain the useful and interfering components at every point of the meshed area, i.e. the aggregate C and I, respectively. In this work, based on the time instant, t , in which each signal arrives at every receiving location, the receiver mask in (3.1) weighs up the completely or partially contribution of each signal to the C and I components,

$$\omega_n = \begin{cases} \left((T_u - t) / T_u \right)^2 & \text{if } (T_g - T_p) < t \leq 0 \\ 1 & \text{if } 0 < t \leq T_g \\ \left((T_u + T_g - t) / T_u \right)^2 & \text{if } T_g < t \leq T_p \\ 0 & \text{otherwise} \end{cases}, \quad (3.1)$$

in which T_u is the useful symbol length; T_g is the guard interval and the time limit during which the echoes can positively contribute to the suitable recovery of the information sent is $T_p = 7T_u/24$, and depend on the DVB-T mode considered.

Moreover, the synchronization strategy chosen for the FFT window positioning at the receiver side also plays a key role as it influences the performance of the OFDM systems in such a way that an efficient technique can lead to a significant reduction of the harmful effect of the pre-echoes and post-echoes arriving at each location.

Once the synchronization strategy and the receiver mask in (1) have been applied, the power sum combination methods can be used to determine the aggregate C and I components at each receiving location. On the one hand, the power sum method is a simple and fast procedure based

on the mean value of the total field strength, which generally provides an overestimation of the final level, but it does not take into account the statistic nature of the received signals at any point inside a local area. On the other hand, regardless of the method, the standard deviation of the individual signals arriving at each point, i.e. the location variation, has been set to $\sigma_n=5.5$ dB. Once the signals have been combined, the carrier to interference-plus-noise ratio, CINR, can be evaluated at each receiving location ($1 \leq r \leq R$) as given in (3.2), considering a SFN consisting of N transmitters, $A=\{1, \dots, N\}$, and that there are other M transmitters from other networks operating at the same frequency, $B=\{1, \dots, M\}$, and working as interferers.

$$CINR_r = \frac{\sum_{n \in A} P_n \omega_n (\delta_n - \delta_0)}{\sum_{n \in A} P_n [1 - \omega_n (\delta_n - \delta_0)] + \sum_{n \in B} P_n + N_0} \quad (3.2)$$

In (3.2), P_n is the power received from the n -th transmitter, ω_n the value of the weighting mask in (3.1) and δ_n the n -th propagation delay related to the synchronization time reference, δ_0 . In this work, the interference from neighboring SFN has been discarded, so the term $\sum_{n \in B} P_n$ in (3.2) has been removed. Moreover, a DVB-T system with an 8 MHz channel along with 10 dB noise figure for the receivers has also been considered, so the background noise power level has been set to $N_0=-99.12$ dBm, assuming an absolute temperature of 290 K. Based on the minimum CINR required at every receiver site to consider that a location is properly covered, $CINR_{min}$, the associated coverage probability, p_c , can be evaluated at that point and thus at every local area, according to (3.3);

$$p_c = Q \left(\frac{CINR_{min} - (m_c - m_i)}{\sqrt{\sigma_c^2 - 2r_{CI}\sigma_c\sigma_i + \sigma_i^2}} \right) \quad (3.3)$$

In (3.3), m_c , σ_c , m_i and σ_i are the means and standard deviations of the aggregate C and I components, respectively, obtained through the combination of the log-normal signals. Moreover, r_{CI} is the correlation coefficient between both C and I components, and Q is the

normalized inverse cumulative distribution function. It must be noticed that in the m_I term it has also been added N_0 .

Finally, this receiver block evaluates the coverage at every receiving location according to the QoS requirements imposed by the user. In this case, every point representing a local area will be considered as covered if the coverage probability, p_c , exceeds a threshold value, $p_{c_{min}}$, which can take two different values, $p_{c_{QoS1}}=90\%$ or $p_{c_{QoS2}}=70\%$ when $CINR_{min}=17.3$ depending on whether the designer has imposed “good” or “acceptable” QoS, and just to distinguish between densely populated and rural areas.

3.3 Spectrum Efficiency

Spectrum efficiency is the efficient way of spectrum or bandwidth usage such that the maximum data transmission can be achieved. Spectrum efficient can be assessed based on efficiency achieved in radio spectrum channel usage. Within the scope of this thesis, the efficiency has been calculated and estimated in terms of channel utilization in regards with the number of TV programs covered as well as for channel utilization in regards with receivers covered which is considered as Multi user channel utilization.

3.3.1 Channel utilization or channel efficiency

It refers to the efficient means of using the transmitter and channel to transmit the data over the channel. Channel Utilization is defined as the ratio of the number of programs covered to the multiplication of the number of channels required and the number of transmitters required in the network.

$$\text{Channel utilization (e)} = N_{pro_cov} / (N_{tx} * N_{ch}) \quad (3.4)$$

Where N_{pro_cov} is the number of programs covered

N_{tx} is the number of transmitters required

N_{ch} is the number of channels required

3.3.2 Multiuser channel utilization

It is defined as the ratio of the number of receivers covered to the multiplication of the number of channels required and the number of transmitters required in the network.

$$\text{Multiuser Channel utilization } (\mu) = N_{\text{Rec_cov}} / (N_{\text{tx}} * N_{\text{ch}}) \quad (3.5)$$

The formula for spectral efficiency can be derived using the equation 1.1 as,

3.4 Use case for channel utilization in MFN and SFN

Within this chapter, simple uses cases for the two broadcasting scheme namely MFN and SFN are presented. With the traditional Frequency Network Planning (MFN) different frequencies are assigned to multiplexes in each neighbor station in the target services area. At a given reception point, the wanted transmitter provides a certain filed strength. Other transmitter stations using the same frequencies provide an interfering contribution.

On the other hand, it is a single frequency network which uses the same frequency in a group of adjacent transmitters to cover a complete or part of a target service area. This is achieved due to the multipath capability of the OFDM signals by the guard interval which makes signal arriving from co-channel transmitters to contribute constructively to the total wanted signal if allowed delays are not exceeded.

The maximum transmitter distances, without causing self-interference, allowed by DVB-T and DVB-T2 are 67.2 km (FFT 8k GI 1/4) and 159.6 km (FFT 32k GI 19/128), respectively, within an 8 MHz RF channel. Given a transmitter distance, self-interference is reduced or eliminated by selecting a larger GI.

These two schemes are presented and explained below:

Scheme 1: Broadcasting over MFN

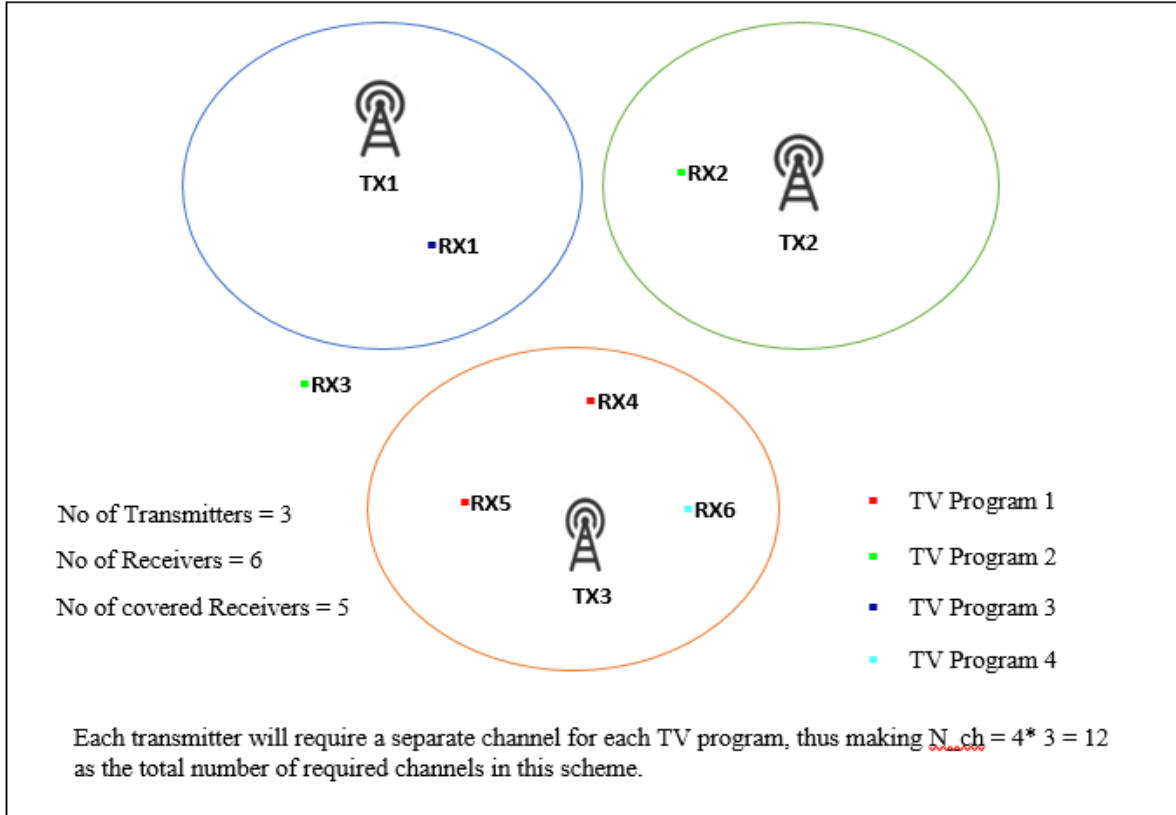


Figure 10 Broadcasting over MFN

In this scheme each transmitter requires a separate channel for each TV program thus making the required channels as $N_{ch} = 4 * 3 = 12$ as shown in the above figure where we have 3 transmitters and 4 TV Programs.

Therefore,

Channel utilization (ϵ) = $4 / (12 * 3) = 0.11$ (using equation 3.4)

Multiuser channel utilization (μ) = $5 / (12 * 3) = 0.13$ (using equation 3.5)

Scheme 2: Broadcasting over SFN

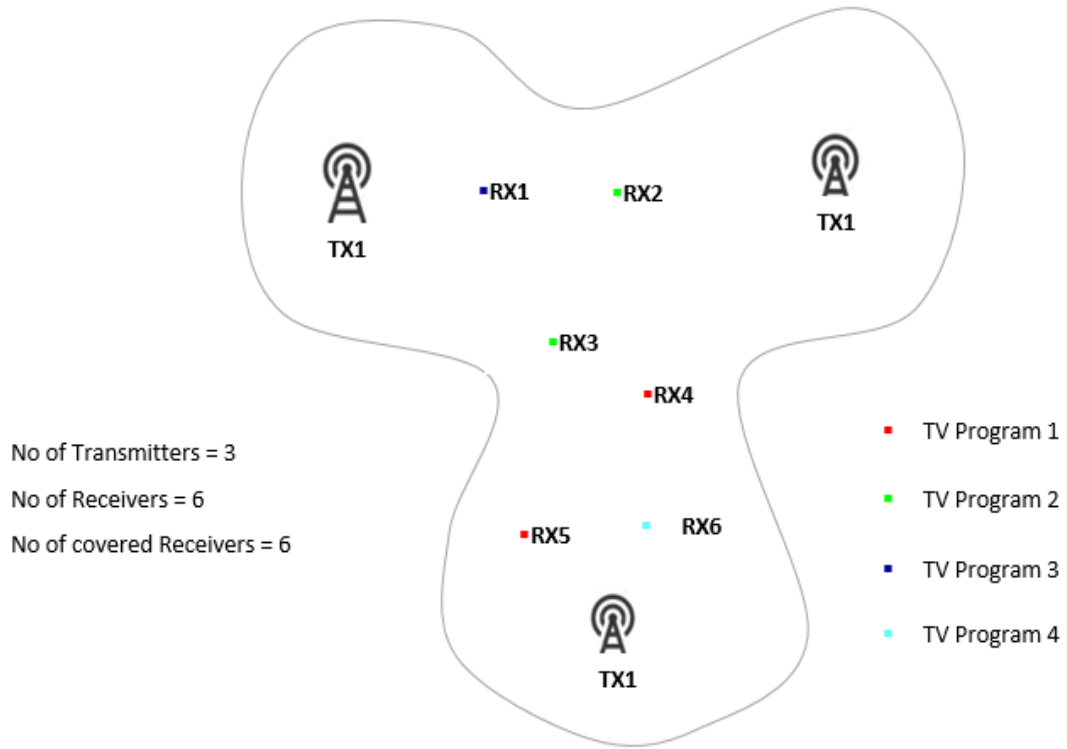


Figure 11 Broadcasting over SFN

In this scheme each transmitter transmits the same TV program over the same frequency at the same time thus making the required channels as $N_{ch} = 4$ as shown in the above figure.

Therefore,

Channel utilization (ϵ) = $4 / (4 \times 3) = 0.33$ (using equation 1.2)

Multiuser channel utilization (μ) = $6 / (4 \times 3) = 0.5$ (using equation 1.3)

From the two above use case for both SFN and MFN, it is clear that there is an improvement in channel utilization efficiency as the channel utilization rise from 0.11 to 0.33 while the Multi user channel utilization rise from 0.13 to 0.5 when shifting from a Single Frequency Network to Multiple Frequency Network.

3.5 Simulation Model

This section provides the simulation model for the two-case study, namely, the MFN case and the SFN case. In the MFN case, different programs are being carried by individual transmitters using different channels, while in the SFN multiple transmitters operate on the same frequency and carrying the same programs. In both cases, we considered a homogeneous network which consists of a single network having multiple transmitters.

3.5.1 Simulation Parameters

Table 2 Simulation parameters and values used

PARAMETER	VALUE
NTx: Number Transmitters	7
NRx: Number of Receivers	35
NCh: Number of Channels	4
Γ : Singal to interference and noise ratio (dB)	1,2,3,4,5,6,7,8,9,10
G : Antenna Gain	$5 \cdot 10^{-4}$
α : Path loss exponents	4
σ : Log-normal fading standard deviation	0dB

3.5.2 Simulation Example

A sample of some 10,000 to 50,000 reception situations, foreach case study in a small area calculation was carried out using the following algorithm:

GIVEN:

- The location statistics of the transmitters
- The location statistics of the receivers
- The channel parameters
- The transmitters parameters
- The receiver parameters

TASKS: To determine the approximate channel utilization defined as the ratio of the number of programs covered to the multiplication of the number of channels required and the number of transmitters required in the network.

1. Using a random number generator, produce a set of NTx transmitter locations
2. Using a random number generator, produce a set of NRx receiver locations
3. Using the channel model calculate the power of the wanted signal C at each receiver locations
4. Calculate the ratio that describe the level of the wanted signal to the level of the interfering signal
5. Given the minimum of the signal to noise ratio, determine for each receiving location where a site is covered by a digital broadcast service or not, we know that the level of the wanted signal, expressed in dB, has to be higher than the level N of noise by a certain value which is the minimum
6. Calculate the channel utilization

3.5.3 Simulation Results

In this section, the channel utilization for both the SFN case and Non-FSN case are presented for a minimum value of SINR value of 10dB and 16dB.

Figure 10 illustrate the channel utilization for MFN and SFN with different number of transmitters when the minimum level of ratio of wanted signal to interfering signal is fixed at 10dB.

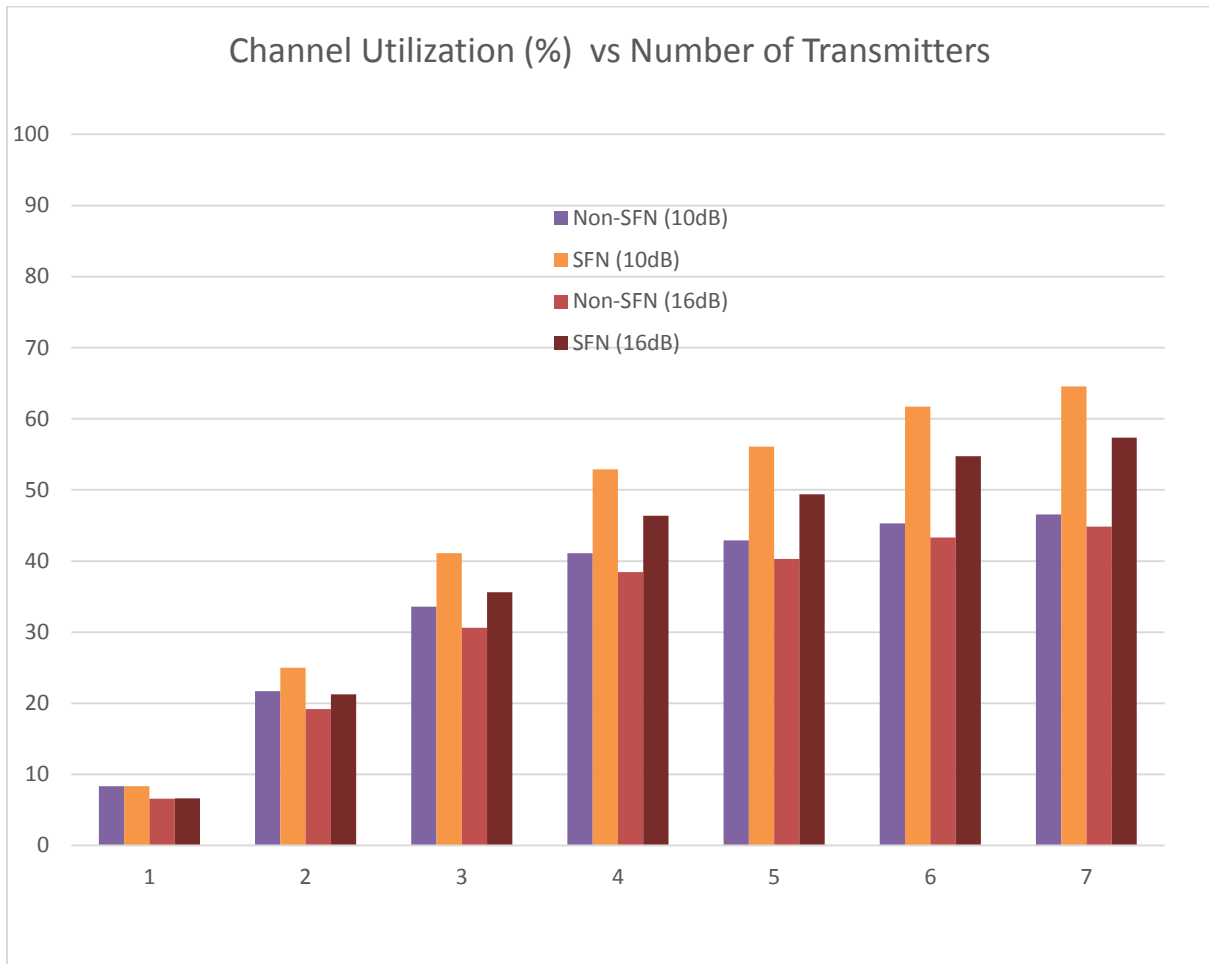


Figure 12 Channel utilization (%) vs Number of transmitter when SINR is set at 10dB

The y-axis represents the channel utilization and the x- axis represent the number of transmitters. From the figure it is seen that, the channel utilization between SFN and MFN increases with the number of transmitters. However, the SFN provides a significant improvement toward the channel utilization as compared with the MFN mode as the number of transmitter increases. For scenario where a TV program has strict requirement for reception i.e with high SINR (16dB), the improvement of channel utilization is very little.

In figure 11, the channel utilization is calculated for a fixed number of transmitter $NT_x = 3$, while the minimum level of wanted signal to interfering signal SINR varies from 0dB to 10dB. As observed from the figure 11, SFN offer more channel utilization than MFN. However, the requirement for data rate is high (SINR high) then more spectrum become wasted because of the high level of interfering signal compared to the wanted signal.

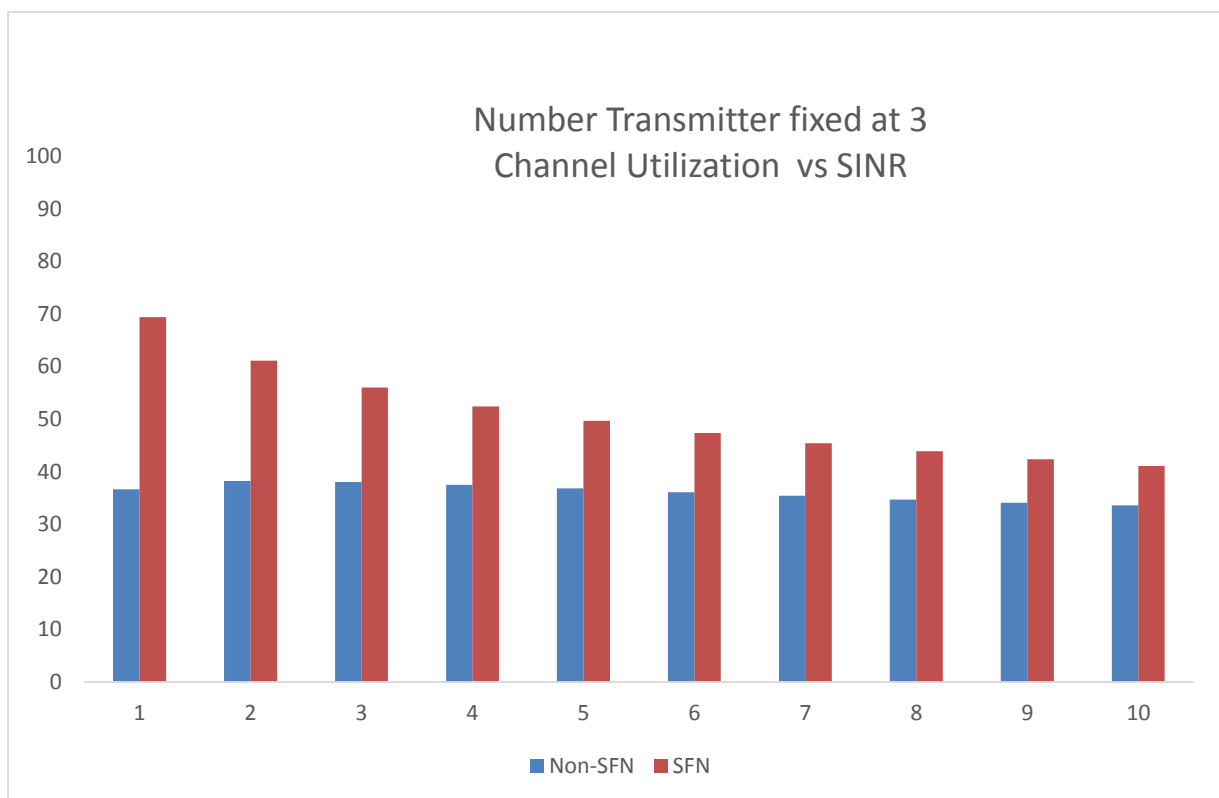


Figure 13 Channel utilization vs SINR when the number of transmitter is fixed at 3

CHAPTER IV. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

In this study it has been demonstrated that with Single Frequency Network a remarkable spectrum efficiency can be used due to the fact that SFN allow coverage of large areas by occupying only a single frequency. This allows huge frequency economic planning possibilities for large broadcasting landscapes.

It has been shown that also a significant improvement in spectrum efficiency is achieved compared to MFN when the numbers of transmitters being used also increases. And with SFN, frequencies that were assigned to a particular site can be shared to different sites in the same service area of the Single Frequency Network accommodating these sites, and in some cases the Network might get above 40% increment which is a remarkable achievement.

The Single Frequency Network also allows success improvement of coverage owing to the properties of the system where receivers in SFN can use all signals received within the allowed interval in a constructive manner.

In addition, SFNs also bring the benefit of space diversity due to the fact that transmitters are located at different locations in the network. The diversity effect, resulting from the fact that the probability of simultaneous shadowing in the presence of several signals is much lower than the probability of shadowing for a single signal, hence contributing to an additional network gain.

4.2 Recommendation

With the above highlighted findings, it is worth mentioning that the implementation of Single Frequency Network shall be a good and interesting undertaking to be adopted by the Broadcasting industry in Rwanda as it can address the issue of spectrum scarcity in the Broadcasting sector.

We therefore propose that consultation with the broadcasting industry be initiated to explore all regulatory and administrative concerns that can be brought by the introduction of Single Frequency Network including additional frequency coordination process with neighboring countries to ensure operationalization in interference free environment. The regulator shall revise the existing broadcasting regulations and introduce new legal and regulatory framework as well as incentive encouraging the implementation of Single Frequency Network.

It is also important to note that the implementation of Single Frequency Network will require more planning and additional financial resources as new investment will be done to upgrade the existing broadcasting systems, hence a reasonable timeframe shall be set to ensure a smooth transition.

REFERENCES

- [1] R.Beutler, "Frequency Assignment and Network Planning for Digital Terrestrial Broadcasting Systems", Kluwer Academic Publishers, 2004
- [2] Zhang, C., Owens, T.J., and Song T-Y, "On the performance of densified single frequency networks for DVB-H", International Journal of Mobile Network Design and Innovation, Vol. 1, Issue 3/4, March 2003
- [3] European Telecommunications Standard Institute: Digital Video Broadcasting (DVB), "Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television," EN 300 744 V1.2.1, July 1999
- [4] R. Beutler, "Digital Terrestrial Broadcasting Networks", Springer, 2008
- [5] ETSI, "Radio broadcast systems; Digital Audio Broadcasting (DAB) to mobile, portable and fixed receivers," ETSI document Draft prevision ETS 300 401, Mar. 1994.
- [6] ETSI, "Digital Video Broadcasting (DVB); Framing structure channel coding and modulation for digital Terrestrial television (DVB-T),"ETS 300 744, Nov. 1996.
- [7] M. Alard and R. Lassalle, "Principles of modulation and channel coding for digital broadcasting for mobile receivers," EBU Technical Review, Aug. 1987.
- [9] R. Hopkins, "Digital terrestrial HDTV for North America – The Grand Alliance HDTV system," EBU Technical Review, Summer 1994.
- [10] B. Fox, "Digital TV comes down to earth," IEEE Spectrum, Oct. 1998.
- [12] V. Mignone, A. Morello, and M. Visintin, "An Advanced Algorithm for Improving DVB-T Coverage in SFN," in Proc. International Broadcasting Convention, Sep. 1997.
- [13] ETSI TR 101 211: "Digital Video Broadcasting (DVB); Guidelines on implementation and usage of Service Information (SI)".
- [14] Brugger, R., "Guard Interval and Coverage Probability in OFDM Single Frequency Networks for terrestrial digital television", GTR2/DTV 156, August 1994.

- [15] European Broadcasting Union, “Guide on SFN Frequency Planning and Network Implementation with regard to DAB and DVB-T”, BPN066 Issue 1.0, Brussels July 2005.
- [16] TERACOM SR, “Digital Terrestrial Television Coverage in a single frequency networks”, Document 11-3/49-E, October 1994.
- [17] Russel, M. Stüber, G. L., Terrestrial Digital Video broadcasting for mobile reception using OFDM”, Kluwer, Wireless Personal Communications, Vol2. Issue ½, 1996.
- [18] Angueira, P.; Velez, M. M.; De La Vega, D.; Arrinda, A.; Landa, I.; Ordiales, J. L.; Prieto, G.; "DTV (COFDM) SFN signal variation field tests in urban environments for portable outdoor reception," Broadcasting, IEEE Transactions on , vol. 49, no. 1, pp. 81- 86, Mar 2003
- [19] ETSI, “Digital Video Broadcasting, Implementation Guidelines for DVB Terrestrial Service, Transmission Aspects”, Cedex-France 2011
- [20] J.-T. Wang, J. Song, J. Wang, C.-Y. Pan, Z.-X. Yang, and L. Yang, “A general SFN structure with transmit diversity for TDS-OFDM system,” IEEE Trans. Broadcasting, vol. 52, no. 2, pp. 245–251, June 2006.
- [21] A. Dammann and S. Kaiser, “Standard conformable antenna diversity techniques for OFDM systems and its application to the DVB-T system,” in IEEE Globecom, Nov. 2001, pp. 3100–3105.
- [22] BUREL, G., MAGNIEZ, P. Transmitters separation for Single Frequency Networks. In Proceedings of IEEE Conference - SPAWC. Anapolis (USA), 1999.
- [23] ITU, “GE06 Agreement: Final Acts of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting service in parts of Regions 1 and 3, in the frequency bands 174-230 MHz and 470-862 MHz (RRC-06)”, ITU, Geneva, 2006
- [24] S. I. Park, S. R. Park, H. Eum, J. Young Lee, Y.-T. Lee, and H. M. Kim, “Equalization on-channel repeater for terrestrial digital multimedia broadcasting system,” IEEE Trans. Broadcast., vol. 54, no. 4, pp. 752–760, Dec. 2008.

- [25] European Telecommunications Standard Institute: Digital Video Broadcasting (DVB), “Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television,” EN 300 744 V1.2.1., July 1999.
- [26] “VHF/FM Planning Parameters and Methods”, EBU-Technical CentreTech. 3236-E, July 1982.
- [27] R. Brugger and D. Hemingway, “OFDM receivers - Impact on coverage of inter-symbol interference and FFT window positioning”, EBU Tech.Rev.295, Geneva, July 2003.
- [28] G. Santella, R. D. Martino, and M. Ricchiuti, “Single frequency network (sfm) planning for digital terrestrial television and radio broadcast services: The Italian frequency plan for t-dab,” in Veh. Technol. Conf., May 17–19, 2004, vol. 4, pp. 2307–2311.
- [29] A. Ligeti, “On Coverage Optimization in Single Frequency Network for Digital Broadcasting using Simulated Annealing,” in Proc. Nordic Radio Symposium, April 1995.
- [30] A. Ligeti, “Coverage Probability Estimation in Single Frequency Networks in the Presence of Correlated Useful and Interfering Components”, in *50th Vehicular Technology Conference, VTC-99 Fall*, Sept. 1999, pp. 2408–2412.
- [31] European Telecommunication Standard Institute , “Radio broadcast systems; Digital Audio Broadcasting (DAB) to mobile, portable and fixed receivers,” ETSI document, Draft prevision ETS 300 401, March 1994.
- [32] D. Plets, W. Joseph, P. Angueira, J.A. Antonio`, L.Verloock and L.Martens, “On the methodology for calculating SFN gain in digital broadcast systems,” IEEE Trans. Broadcast., vol. 56, no. 3, pp. 331-339, Sep. 2010.
- [33] Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000 MHz, Recommendation ITU-R P.1546-4, Oct. 2009.
- [34] A path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands, Recommendation UITR P.1812-2, Feb. 2012.