**Mid Sweden University**  
The Department of Information Technology and Media (ITM)  
Author: S.M. Hasibur Rahman  
E-mail address: hasibur.rahman29@yahoo.com  
Study programme: Computer Engineering, 120 credit points  
Examiner: Dr. Tingting Zhang, tingting.zhang@miun.se  
Tutor: Magnus Eriksson, Mid Sweden University, magnus.eriksson@miun.se  
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**IP Multicasting over DVB-T/H and eMBMS**  
Efficient System Spectral Efficiency Schemes for Wireless TV Distributions

S.M. Hasibur Rahman
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Abstract

In today’s DVB-T/H (Digital Video Broadcasting-Terrestrial/Handheld) systems, broadcasting is employed, meaning that TV programs are sent over all transmitters, also where there are no viewers. This is inefficient utilization of spectrum and transmitter equipment. IP multicasting is increasingly used for IP-TV over fixed broadband access. In this thesis, IP multicasting is proposed to also be used for terrestrial and mobile TV, meaning that TV programs are only transmitted where viewers have sent join messages over an interaction channel. This would substantially improve the system spectral efficiency (SSE) in (bit/s)/Hz/site, allowing reduced spectrum for the same amount of TV programs. It would even further improve the multiuser system spectral efficiency (MSSE – a measure defined in this study), allowing increased number of TV programs to be transmitted over a given spectrum. Further efficiency or coverage improvement, may be achieved by forming single-frequency networks (SFN), i.e. groups of adjacent transmitters sending the same signal simultaneously, on the same carrier frequency. The combination of multicasting and SFNs is also the principle of eMBMS (evolved Multicast Broadcast Multimedia Service) for cellular mobile TV over 4G LTE. PARPS (packet and resource plan scheduling) is an optimized approach to dynamically forming SFNs that is employed in this study. The target applications are DVB-T/H and eMBMS. Combining SFNs with non-continuous transmission (switching transmitters on and off dynamically) may give even further gain, and is used in LTE, but is difficult to achieve in DVB-T/H. Seven schemes are suggested and analyzed, in view to compare unicasting, multicasting and broadcasting, with or without SFN, with or without PARPS, and with or without continuous transmission. The schemes are evaluated in terms of coverage probability, SSE and MSSE. The schemes are simulated in MATLAB for a system of 4 transmitters, with random viewer positions. Zipf-law TV program selection is employed, using both a homogeneous and heterogeneous user behavior model. The SFN schemes provide substantially better system spectral efficiency compared to the multi-frequency networks (MFN) schemes. IP multicasting over non-continuous transmission dynamic SFN achieves as much as 905% and 1054% gain respectively in system spectral efficiency and multiuser system spectral efficiency, from broadcasting over MFN, and 425% and 442% gain respectively from IP multicasting over MFN, for heterogeneous fading case. Additionally, the SFN schemes gives a diversity gain of 3 dB over MFN, that may be utilized to increase the coverage probability by 4.35% for the same data rate, or to increase the data rate by 27 % for the same coverage as MFN.

Keywords: IP multicasting, broadcasting, coverage probability, system spectral efficiency, multiuser system spectral efficiency, DVB-T/H, eMBMS, mobile TV, IP-TV, SFN, MFN, Dynamic SFN, PARPS, homogeneous, heterogeneous, zipf-law
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## Terminology

### Acronyms

- **DVB-T**: Digital Video Broadcasting-Terrestrial
- **DVB-H**: Digital Video Broadcasting-Handheld
- **eMBMS**: evolved Multimedia Broadcast Multicast Service
- **COFDM**: Coded Orthogonal Frequency Division Multiplexing
- **SFN**: Single Frequency Network
- **MFN**: Multi Frequency Network
- **DSFN**: Dynamic Single Frequency Network
- **CT-DSFN**: Continuous Transmission Dynamic Single Frequency Network
- **NCT-DSFN**: Non-Continuous Transmission Dynamic Single Frequency Network
- **PARPS**: Packet And Resource Plan Scheduling
- **UDP**: User Datagram Protocol
- **IGMP**: Internet Group Management Protocol
- **LTE**: Long Term Evolution
- **OTA**: Over-the-Air Television
- **TDM**: Time-Division Multiplexing
- **FDM**: Frequency-Division Multiplexing
- **MS**: Mobile Station
- **BS**: Base Station
- **Tx**: Transmitter
- **Rx**: Receiver
- **RNC**: Radio Network Controller
- **BTS**: Base transceiver Station
- **MPE-FEC**: Multiprotocol Encapsulation Forward Error Correction
- **MBSFN**: Multimedia Broadcast Single Frequency Network
- **MCE**: Multi-Cell/Multicast coordination
- **BMSC**: Broadcast/Multicast service center
- **RRM**: Radio Resource Management
- **DCA**: Dynamic Channel Allocation
- **SNR**: Signal-to-Noise Ratio
- **SINR**: Signal-to-Interference-Noise Ratio
- **ISI**: Inter Symbol Interference
- **BER**: Bit Error Rate
- **QPSK**: Quadrature Phase Shift Keying
- **QAM**: Quadrature Amplitude Modulation
- **LSA**: Local Service Area
- **MIP**: Megaframe Initialization Packet
- **TS**: Transport Stream
- **IPTV**: Internet Protocol Television
Terminology

Mbp s  Mega bit per second
MHz   Mega Hertz
CoMP  Coordinated Multi-Point
UE    User Equipment
MIMO  Multi Input Multi Output
RRE   Radio Resource Equipment
JP    Joint Processing
CS/CB Coordinated Scheduling/ Coordinated Beamforming
SSE   System Spectral Efficiency
MSSE  Multiuser System Spectral Efficiency

Mathematical Notation

\( P \) Power
\( i \) Transmitter Position
\( j \) Receiver Position
\( F \) Fading
\( G \) Antenna Gain
\( d \) distance
\( n \) noise level
\( Cp \) Coverage Probability
\( N_{\text{ch}} \) Number of Channel
\( N_{\text{Rx}} \) Number of Receivers
\( C_{\text{Rx}} \) Covered Receivers
\( \alpha \) Propagation path loss constant
\( \Gamma \) SINR
\( \theta \) Exponent value of characterizing zipf distribution
\( R \) Radius
\( \eta \) System Spectral Efficiency
1 Introduction

*IP multicasting* has been a popular technique for efficient distribution of TV programs for IP-TV over fixed broadband access. In this thesis, a novel idea is proposed and investigated which is to apply IP multicasting to the terrestrial and mobile TV as contrary to today’s broadcasting. The idea is that TV programs will only be transmitted if viewers currently exist. Examples of such wireless technologies include *DVB-T* (digital video broadcasting- terrestrial) (see section 2.7), *DVB-H* (DVB -handheld) (see section 2.8), and *eMBMS* (evolved multimedia broadcast multicast service) (see section 2.13). The advantages of using this new idea are that it would increase the coverage for TV programs and *system spectral efficiency (SSE)*. However, the disadvantage is that it would require a back channel for program selection.

The *Coded orthogonal frequency division multiplexing (COFDM)* splits a high-bandwidth carrier signal into multiple slow low-bandwidth sub-carrier signals. This gives diversity gain in case of multipath propagation, and also useful for adaption to different channel conditions. This is also extremely useful for efficient management of bandwidth and extensively used in many wireless systems. COFDM allows *single frequency network (SFN)* (see section 2.2). The SFN implies that several transmitters use single frequency for the same signal at the same time. This is very helpful to efficiently manage radio spectrum, to increase the coverage area, etc. An SFN can provide higher number of radio and TV programs compared to a *multi frequency network (MFN)* in the same spectrum. SFN can be used dynamically i.e. SFN formations can be changed according to the need of the network in different timeslots. This is known as *dynamic SFN (DSFN)* (see section 2.3). DSN is further divided into *continuous transmission DSFN (CT-DSFN)* and *non-continuous transmission DSFN (NCT-DSFN)*. To manage these DSFN variants, a dynamic radio resource management called *packet and resource plan scheduling (PARPS)* (see section 2.14) algorithm is suggested. In PARPS, resource plans are changed in different timeslots without calculating the signal-to-interference ratio for every individual packet. DSFN is also beneficial for providing improved spectral efficiency. eMBMS may use NCT-DSFN.

On the other hand, IP multicasting is a point-to-multipoint communication method. IP multicasting provides more advantages than unicasting and broadcasting. Unicasting requires dedicated radio channel for each receiver whereas broadcasting means signal is transmitted to the all receivers in the network. This is very inefficient in terms of radio spectrum management. IP multicast provides an efficient way of managing the spectrum. In IP multicasting, the signal is transmitted to a group of receivers in the network. Thus no spectrum is wasted. IP multicasting uses *user datagram protocol (UDP)*. If a receiver wants to join or leave a network, then that
receiver must send a message to the network. This is achieved by internet group management protocol (IGMP). IGMP keeps track of multicast membership in the network.

The wireless TV distribution networks DVB-T and DVB-H are used for digital video broadcasting. DVB-T is a term mostly used in Europe, in the USA it is commonly known as broadcast television or over-the-air television (OTA). DVB-T is expected to be ubiquitous in Europe by 2012 once analogue television becomes completely extinct. DVB-T is implemented over radio waves using the COFDM modulation scheme. COFDM allows DVB-T to use SFN. Thus DVB-T provides efficient use of spectrum. DVB-H technically is an extension to the DVB-T, but used for battery powered handheld devices i.e. cellular phones or handsets.

eMBMS is expected to be very useful for long term evolution (LTE) 4G networks as a one-to-many communication system. This would enable LTE to provide multicast and broadcast services along with the regular unicast services. eMBMS is supposed to provide spectral efficiency to the LTE by utilizing session-set up scenario for each multicasting service. For multicasting and broadcasting, eMBMS may utilize SFN with OFDMA radio resources.

1.1 Background and problem motivation

IP multicasting is already being used in fixed broadband access; however, this concept was never used in wireless TV distribution. The idea of using IP multicasting over DVB-T and DSFN was proposed by Magnus Eriksson at Mid Sweden University in the year 1997 and a thesis work on the same title was carried out by Muhammad Ashfaq Malik last year (2011) at Mid Sweden University. Aim of this thesis is to address the suggestions for future work made by Muhammad Ashfaq Malik and further improve his work. Furthermore, eMBMS which is designed to be used in 4G LTE networks for multicast broadcast service will be explored in this work. In future, more TV programs are expected to be in the market. Cell phones are already widespread and are increasing in numbers. Most cell phones have the facility of mobile TV which makes wireless TV a popular mode of service. eMBMS is expected to contribute to this cause, this will be particularly helpful in live events such as live concert, sports etc. However, different people have different choice of TV programs. IP multicasting is believed to be a helpful and efficient technique to provide TV services. TV service provider would only transmit the TV programs that viewers’ are interested currently in watching. This will allow efficient management of spectrum as opposed to broadcasting where spectrum would have been wasted if viewers do not exist for the broadcasted TV program(s). The challenge for IP multicasting is that users would require a back channel for program selection. Since cell phones do have back channel readily available, IP multicasting is feasible on cell phones. In this work, the aim is to analyze different schemes of transmitting wireless TV programs.
and to find out which scheme offers better system spectrum efficiency and coverage probability. A total of seven schemes will be explored.

1.2 Overall aim
Since spectrum is wasted in wireless broadcasting TV distribution, multicasting would offer enhanced spectrum management. Moreover, two of the most important aspects of wireless networks are coverage probability and efficient management of spectrum. The objective of this thesis, therefore, is to study the efficient management of spectrum in different proposed schemes and to increase the coverage probability in order to reduce the outage probability.

1.3 Scope
The scope of this thesis is introduction of IP multicasting to the wireless TV distribution. By utilizing IP multicasting and dynamic SFNs in the wireless TV distribution, the spectrum can be managed efficiently and outage probability can also be reduced which will increase the coverage probability. The idea is that IP multicasting will reduce the channel requirement as TV programs will only be transmitted if currently viewers for that particular program exist. By reducing the number of channels requirement for transmitting a certain number of TV programs, spectrum efficiency will be gained. Here, channels can be referred to timeslots or frequency channels, for example, time-division multiplexing (TDM) or frequency-division multiplexing (FDM) channels. Moreover, SFN will reduce the outage state probability by increasing the coverage probability. Then two variant of DSFN will also be investigated to further enhance the spectrum efficiency.

1.4 Concrete and verified goals
As stated previously, different schemes of distributing TV programs over the wireless medium will be designed and analyzed. The schemes that will be designed and analyzed are: Scheme A: Unicasting over MFN, Scheme B: Broadcasting over MFN, Scheme-C: IP Multicasting over MFN, Scheme-D: Broadcasting over SFN, Scheme-E: IP Multicasting over CT-DSFN, Scheme-F: IP Multicasting over NON-SFN DCA, and Scheme-G: IP Multicasting over NCT-DSFN. Initially, these schemes will be implemented without taking fading into consideration; later on those schemes will be assessed with the presence of fading. Finally, a comparison of all the schemes will be made based on coverage probability, and system spectral efficiency as a ratio between channel capacity, channel utilization and bandwidth. Further, a new measure in the form of multiuser system spectral efficiency will be defined and evaluated. Efficiency improvement in terms of percentage will also be discussed.

1.5 Outline
The outline of the thesis is portrayed in this section.
Chapter 1 is the introduction to the thesis work. The motivation behind the work and goal of the thesis has been outlined here.

Chapter 2 introduces to the background study related to the thesis. SFN, DSFN, DVB-T, eMBMS, PARPS etc. have been discussed here.

Chapter 3 demonstrates the methodology of this work.

Chapter 4 describes the design of the different schemes. This corresponds to the formations of the schemes and scheduling that will be studied.

Chapter 5 illustrates the random model (Zipf-Law, Homogeneous, Heterogeneous, and Fading model).

Chapter 6 analyzes the results of the thesis.

Chapter 7 discusses the conclusion of the work. The results that have been accomplished and what could make the work better. Some suggestions for future work has been addressed.

1.6 Contributions

This work is an extension to the work by Muhammad Ashfaq Malik and the author has the following new results and methods:

- Scheme-E: IP Multicasting over CT-DSFN (see section 4.1.5)
- Scheme-F: IP Multicasting over NON-SFN DCA (see section 4.1.6)
- Scheme-G: IP Multicasting over NCT-DSFN (see section 4.1.7)
- Fading model (see section 5.4)
- Heterogeneous channel selection model (see section 5.3)
- Several academic papers and standards, especially about eMBMS
2 Theory

This chapter includes the background study related to the work.

2.1 Macro-Diversity

Macro-diversity is a type of diversity scheme which uses several transmitters and receivers for quality transmission. In macro-diversity, two transmitters sending the same signal are separated in way that their distance is longer than the signal wavelength, $\lambda$ [1]. Figure no. 1 demonstrates this fact. If the distance between transmitters (Tx) is $d$, then the value of $d$ is much larger than $\lambda$ ($d \gg \lambda$).

![Figure 1 Macro-Diversity Concept](image)

In cellular network communication, macro-diversity usually signifies the mode where a receiver communicates with various transmitters. Transmitter macro-diversity implies that same signal is transmitted from multiple transmitting stations. In order to combat fading, to enhance the received signal strength and quality, and to increase the transmission coverage area same frequency channel is used. Furthermore, when same frequency is used by the transmitters for the signal transmission then the network is called single frequency network (discussed in the following section). Currently macro-diversity has been employed in some of the latest technologies for example CDMA-2000, UMTS as soft handover (see section 2.4), and DVB-T (see section 2.7), DAB etc. [1].

2.2 Single Frequency Network

Single-Frequency Network (SFN) is a broadcast network used for the efficient transmission of digital content over a specific area and region [4]. As the name SFN indicates, single frequency is used for transmission by various transmitters at the
same time for the same signal transmission. Digital audio broadcasting, digital video broadcasting are some of the applications that use SFN. SFN has some advantages over the traditional multi-frequency network (MFN), for example, efficient use of the radio spectrum, increased coverage area, decreased outage probability, easy gap-filling by reusing frequency, low power operation [2]. An SFN can accommodate higher number of radio and TV programs in the same spectrum in comparison to an MFN. The following figure illustrates the difference between SFN and MFN.

From the above figure it is seen that SFN utilizes only one frequency while MFN requires three frequencies for the cell allocation in this particular example. Although SFN has some obvious advantages, SFN also requires some considerations. Self-interference, transmitter synchronization are two of the main design considerations in SFN. SFN may utilize COFDM modulation which combats for self-interference. As a pragmatic rule, the guard interval should have a value which allows a signal to propagate over the distance between two transmitters of an SFN so that the self-interference cannot cause any harm. If the guard interval is not selected properly then the signal from a far distant transmitter would behave like a noise rather than a wanted signal [2]. Furthermore, SFN adds some extra information to the serial data streams by inserting a time reference signal into the network in order to synchronize the transmitters in both time and frequency domain[2]. An SFN adapter accomplishes this extra information addition which enables the transmitters to be synchronized (see figure 3). SFN requires three conditions to be fulfilled before any transmission can take place. The conditions are [3]:

- The same frequency
- Same time
- Same OFDM symbol
The following section discusses a variant of SFN known as DSFN.

2.3 Dynamic Single Frequency Network

Dynamic Single Frequency Network (DSFN), a transmitter macro-diversity technique, is a special kind of SFN for OFDM based cellular networks communication [5]. In DSFN, network is divided into SFNs. Each SFN is changed dynamically based on scheduled timeslot for the receiver and traffic conditions adoption. By using this technique, OFDM based cellular networks can utilize efficient spectrum for downlink communications, for example, unicast or multicast services. DSFN has more or less the same advantages as SFN. DSFN can be referred as the combination of three other techniques, namely, packet scheduling, macro-diversity, and dynamic channel allocation (DCA). The scheduling algorithm, which is controlled centrally, is used for data packet assignment to a certain timeslot, frequency channel and group of base station transmitters [5]. The modulation scheme and error detection scheme can also be dynamically assigned to each timeslot and transmitter in order to achieve efficient optimization. DSFN can be compared to the CDMA downlink soft handover [5]. However, as CDMA utilizes different spreading codes for different users so it can avoid co-channel interference. DSFN can be further divided into continuous transmission DSFN (CT-DSFN) and non-continuous transmission DSFN (NCT-DSFN). In CT-DSFN, all the transmitters are always on meaning that all the transmitters transmit all the time. Whereas in NCT-DSFN, transmitters are in on-off mode meaning that transmitters do not always transmit. To manage these DSFNs, a special algorithm called PARPS (see section 2.14) is suggested. Figure no. 4 portrays a simple DSFN scenario.
In this above scenario, which resembles CT-DSFN, there are two transmitters (Tx) which are synchronized and centrally controlled, and total of five receivers (Rx). The transmitters form two groups in two different timeslots. At first, transmitters individually form a group and then together another group is formed. It can also be seen that, in the first timeslot each transmitter sends different packets to the receivers (Rx1, Rx2). In the second timeslot, same packets are sent to the receivers (Rx3, Rx4) by the transmitters. However, these groupings cannot cover receiver Rx5 which is in outage state [4].

In the following sections, a number of macro-diversity concepts that resemble DSFN are presented along with some other technologies.

### 2.4 Soft Handover

Soft Handover is a term mostly used in CDMA or W-CDMA standards [29]. In this scenario, a mobile stations (MS) is connected to more than one cell or cell site. This way soft handover diversity gain (see section 2.5) is achieved. It also requires a low power control (see section 2.6) which makes it suitable for powered controlled CDMA systems [30]. Soft handover also occurs when a MS leaves a cell for another cell and the current connection is not terminated before connecting to another cell [31]. The following figure shows such an example in UMTS.
The radio network controller (RNC) is responsible for controlling the NodeBs that are connected to it through the lub interface. Physically, this lub interface can be implemented over the optical fiber [33]. RNC is similar to the base station controller (BSC). NodeB corresponds to the base transceiver station (BTS) in 2G/2.5G networks. In figure 5, the receiver is receiving the signal from both the NodeBs, and the connection to the current NodeB is terminated when the receiver is connected to the other NodeB.

2.5 Diversity Gain
Diversity gain plays an important role in wireless communications by utilizing the MIMO antenna. Without any kind of performance loss, diversity gain increases signal-to-interference ratio and reduces the transmission power [6]. It is usually measured in decibel (dB). However, it can also be measured in terms of power ratio. For selection combining diversity gain, the strongest signal is used.

2.6 Power Control
Power control implies controlling transmission power in order to achieve a good performance in a communication system. The term good performance can be anything in the form of link data rate, network capacity, network coverage area, etc. [7]. Transmission power control plays a key role in interference management, energy management, and connectivity management in wireless networks [15]. For example, in an SFN due to the broadcast nature, signals suffer from co-channel interferences, which can be reduced by careful power control. Power control in the cellular system does have some obvious advantages and disadvantages. If the transmitter power is increased then the signal-to-noise ratio (SNR) becomes higher, which would yield in
reduction in the bit error rate (BER). Higher SNR also increases data rate for a system using link adaption and this also combats against fading [7]. Increasing transmitter power can be a problem for MS where battery discharges all the time, this increase in the transmitter power can also create interference among the users that are using the same channel. Therefore, this power control needs to be handled carefully. Base station (BS) takes care of the transmitted power by the MS. There are some design issues in a cellular system for controlling the power. They are [8]:

- The transmitted power from BS should be adjusted when MS moves
- The transmitted power from MS should be minimized to combat for interference with the channels on the same frequency
- The received power at the BS from all the MS in CDMA should be equalized. This is needed to improve the system performance as they all use the same frequency

2.7 Digital Video Broadcasting - Terrestrial

Digital video broadcasting terrestrial (DVB-T), as the name suggests, is a digital video broadcasting service implemented over the radio waves and it does not involve satellite or cables. This term is commonly used in Europe, in the USA this is known as broadcast television or over-the-air television (OTA) [9]. The DVB-T standard was first published in the late twentieth century and is expected to become ubiquitous by 2012, once the analog transmission is completely diminished in Europe. The DVB-T uses the MPEG transport stream (MPEG-TS) to deliver digital audio, video and other data using the COFDM modulation scheme [9]. The DVB-T MUX center receives MPEG-TS with TV services from the TV production centers. It inserts the service information (PSI/SI tables) and multiplexes the services into a single MPEG-TS. An DVB-T can use either of the 2K or 8K OFDM sub-carrier modes and utilizes the efficient quadrature modulation schemes (QPSK, 16-QAM, 64-QAM) [9]. 2K and 8K correspond to the 2048 and 8192 OFDM sub-carriers respectively, however, DVB-T actually makes use of 1705 sub-carriers of 2K mode and 6817 sub-carriers of 8K mode [14]. It transmits data in a series of discrete blocks with guard interval between the symbols [9]. SFN can also be used for datacasting the same data in a certain area of DVB-T. This area (SFN over DVB-T) is known as local service area (LSA). This use of SFN leads careful design consideration for DVB-T as synchronization is necessary for SFN. The synchronization information is inserted into the MIP (Megaframe Initialization Packet). The MIP is a special MPEG packet inserted into the MUX center. There are two transmitter synchronization issues namely time and frequency synchronization. Time synchronization means that DVB-T transmitters would broadcast at the same time and frequency synchronization refers to the fact that all the transmitters broadcast the same set of sub-carriers [3]. After receiving the MPEG-TS(s), the transmitters have to wait to receive a MIP and then calculate the delay they need to wait until they can transmit the first bit of that megaframe. Network delay is equalized with the time stamps in the MIP packets by making all transmitters wait
The maximum delay that TSs supports is around 1 second. DVB-T has been adopted in many other parts of the world like in Asia and Australia. Lately, two new variants of DVB-T have been standardized namely DVB-Handheld (DVB-H) (discussed in section 2.8) and DVB-T2. The DVB-T2 offers many benefits than the DVB-T. In addition to 2K and 8K OFDM mode, DVB-T2 uses 1K, 4K, 16K, and 32K OFDM mode. It also utilizes the 256-QAM modulation scheme along with the existing modulation schemes for DVB-T. The DVB-T2 offers more capacity than the DVB-T. DVB-T offers 24 Mbit/s, on the other hand DVB-T2 offers 36.1 Mbit/s [38]. Furthermore, DVB-T2 supports dynamically variable modulations and FEC, which enables mobile and fixed services in same bandwidth, and directly supports non-TS formats e.g. IP [38]. Mobile services further enable time and frequency sliced services. Figure no. 6 illustrates a DVB-T system.

The above figure shows that video/audio is generated in the TV studio which is then fed into the antennas. Antennas then deliver the audio/video to the terrestrial TV sets. This figure also demonstrates that a DTV IP-Inserte (corresponds to the MUX center) is installed in front of each antenna, which could be used to insert any local data along with the original content, for example, city guides, restaurant information, sports and weather news, etc. [10]. A DTV IP-Inserte can be shared by LSAs for a group which is interested in similar data. Some of the applications are: datacasting, multicasting of IP-TV (see section 2.9), unicasting of interactive TV etc. Multicasting of IP-TV and unicasting of interactive TV requires a back channel.
2.8 Digital Video Broadcasting- Handheld

Digital video broadcasting- handheld (DVB-H) is intended for battery powered devices, and, technically speaking, an extension to the DVB-T. DVB-H is suitable for mobile broadcasting and is adopted by the European Union in March, 2008 [11]. It is compatible with the DVB-T, but DVB-H provides some advantages over the DVB-T. For example, DVB-H uses time-slicing for reducing the power consumption, makes use of multiprotocol encapsulation forward error correction (MPE-FEC) which makes the system more robust in providing better signal reception, introduces 4K carrier mode which helps in network optimization [13]. There are also few requirements for DVB-H, for example, quality should be at some acceptable level for broadcast services; service should be available while moving and handover from cell to cell; a coverage area as mobile radio; should share network and transmission tools [11]. DVB-H can afford to provide data rates as high as 10 Mbps and can make use of 5 MHz, 6 MHz, 7 MHz, and 8 MHz channels [12]. For the modulation scheme, it utilizes the quadrature modulation schemes (4-QAM, 16-QAM, 64-QAM), and it has 2K, 4K and 8K COFDM carrier modes. The following figure depicts a DVB-H broadcast network.

Figure 7 DVB-H broadcast network [13]

2.9 Internet Protocol Television

Internet protocol television (IPTV) is another technique delivering television services to the users. It uses the internet protocol suite to distribute the service to the users over ADSL modem or fiber-to-the-home. However, this term should not be confused with internet-television which basically unicasts television over the internet. IPTV has several modes of services: live television, current TV programs are shown; time-shifted video-on-demand, replays of the old programs that are multicasted; video-
on-demand unicasting, list of shows are provided and users choose their content to view [16]. The increase in the internet speed and availability of high bandwidth made IPTV feasible. More often than not the internet service provider makes this service available along with the broadband service. Typically, the users required to have a set-top box and a home gateway along with the TV sets or any means that can encode TV signals. The success of IPTV depends on the market demand and the operator’s capability to provide interactive contents to the end users.

2.10 Virtual Cellular Network

Virtual cellular network (VCN) is a wireless communication architecture suggested in 1990s, which is aimed at providing services in the wireless network. It does not use the traditional cellular frequency reuse method or the base stations pattern, rather utilizes the whole transmission bandwidth, and receiver ports along with port server. VCN has some advantages: increases the user capacity and coverage, simplifies protocol for power consumption, provides frequency efficiency, matches heterogeneous network, etc. [17]. VCN can be compared with the continuous transmission DSFN, and it was originally aimed at spread-spectrum techniques but now also suggested for OFDM. VCN and OFDM together can be viewed as DSFN. Figure 8 depicts a virtual cellular network. This VCN consists of five terminals (a,b,e), few ports (A, B, ...), few virtual cells (the circles denote the virtual cells), a port server. The ports are connected to the port server through the network [17]. Each virtual cell forms an SFN.

![VCN Diagram](image)

2.11 Cooperative Diversity

Cooperative diversity is a cooperative antenna technique for wireless multi-hop networks and other relay networks, for example, can be used in LTE, which uses multiple wireless network nodes. This technique utilizes the fact that the system has
a source, relay stations, and a destination, for example, a multihop network. Cooperative diversity decodes the combined signal from a source and relay stations. Relayed signals are considered as a contribution to the direct signal whereas, in the non-cooperative system, the source signal is viewed as interference. This way cooperative diversity improves or maximizes the signal quality. This can also be thought as a user cooperation system which implies that the user relays other users’ signals. There are three relaying strategies employed by this system namely decode-and-forward, amplify-and-forward, and compress-and-forward [18]. Amplify-and-forward is the best as guarantees full diversity [19]. There are two relay transmission topologies namely, serial and parallel relay transmission. In serial relay transmission, the signal is propagated between relays one by one and orthogonality between the relay channels ensures no interference. This topology is basically used for long distance communication and provides the power gain. However, it suffers from multi-path fading. Parallel relay transmission, in contrast, provides robustness against multi-path fading, and achieves both power and diversity gain. Signal is combined by the destination after signal is propagated through multiple hops. Furthermore, for decoding there are four approaches. Direct scheme, non-cooperative scheme, cooperative scheme, and adaptive scheme are the approaches for decoding. Only the direct scheme does not employ any relay station. Cognitive radio system, wireless ad-hoc networks, wireless sensor networks are some of the applications for cooperative diversity [18]. The following figure gives an idea of a cooperative diversity system.

![Cooperative Diversity System](image)

The above cooperative diversity system has only one relay station, however, if there is more than one relay station as shown in figure no. 10, then the signals from these relay stations can be formed together to constitute an SFN. Hence, the synchronization of the relayed signals can be ensured. If one or two relay stations are switched off during transmission, then it resembles the DSFN.
2.12 Coordinated Multi-Point Transmission/Reception

Coordinated multi-point (CoMP) transmission and reception is a standard for LTE and 3G networks [22]. It provides dynamic coordination between multiple cells and receives/transmits signals from/to single user equipment (UE) by utilizing MIMO antenna system [21]. This MIMO antenna might belong to a single cell or more than one cell [21], which gives macro-diversity i.e. DSFN, for unicasting. The prime objective of CoMP is to make sure that UEs at the edge of cells are not affected by the cell interference. This is achieved by coordinating between cells, and the edge-cell UE is served by various cells (see figure no. 11). Also the multiple transmission and reception antenna makes CoMP to provide other advantages such as coverage improvement, system efficiency, and cell-edge throughput [21].
CoMP can be implemented in two ways: autonomous control based or centrally controlled based (see figure no. 12). In autonomous control based CoMP, there is an independent eNodeB which employs wired transmission to communicate among the cells. The regular cell configuration can be utilized for wired signaling communication; however, the drawback with this approach is that it leads to signaling delay and overhead. To minimize this problem, the centrally controlled approach employs several radio resource equipments (RRE). The RREs are connected using optical fibers. The central eNodeB controls the radio resources between cells. However, the weakness of this approach is that as the number of RRE increases the optical fiber load also increases. Therefore, it is important to utilize both approaches as appropriate and both have been studied for their use in 4G LTE [22].

CoMP is used for uplink reception and downlink transmission [22]. In the uplink reception, several cells receive the signal from a UE and combine them. Cell-edge throughput is achieved in this way. As for the downlink transmission, there are mainly two types namely joint processing (JP) and coordinated scheduling/coordinated beamforming (CS/CB) [22] (see figure no. 13). JP utilizes two techniques dynamic cell selection and joint transmission. In dynamic cell selection only one cell transmits data (see figure no. 13(b-2)) and in joint transmission multiple cells transmit data (see figure no. 13(b-1)). Thus, dynamic cell selection resembles NON-SFN DCA and joint transmission resembles CT-DSFN. Joint transmission can be further divided into coherent/non-coherent transmission. JP is responsible for transmission gain which is accomplished by the joint transmission. In CS/CB, only one eNodeB transmits data but cells are connected to each other (see figure no. 13(a)). This cell connection allows the exchange of information regarding scheduling and beamforming. This multi-cell
dynamic scheduling combats for cell interference. Furthermore, this dynamic scheduling resembles DSFN.

![CoMP Downlink Transmission Types](image)

**Figure 13 CoMP Downlink Transmission Types [22]**

### 2.13 Evolved Multimedia Broadcast Multicast Services

An evolved multimedia broadcast multicast services (eMBMS) is a point-to-multipoint technology designed to be used in LTE (4G) networks. This has been standardized in the 3GPP Release-9 [24]. This will enable LTE to provide multicast and broadcast services along with the regular unicast services. This will be particularly helpful for live programs such as sports, concert etc. Technically speaking, eMBMS is expected to provide more benefits to the LTE than MBMS was supposed to do in GSM and UMTS networks. LTE will have much more spectral efficiency as well as the reduction in the cost per bit. eMBMS is expected to get rid of dedicated spectrum by utilizing the session set up scenario. It will create a new session to use the network resources for each multicasting and will return once the session expires. This session set-up scenario can be viewed as NCT-DSFN as the signal is transmitted when required. Therefore, the efficient use of spectrum can be ensured. Another advantage of eMBMS is that it may transmit over SFN for multicasting or broadcasting by using the OFDMA radio resources [25]. This term is called multimedia broadcast single frequency network (MBSFN). In MBSFN, there are several cells which are tightly synchronized and transmit MBMS data to the UE. Several cells usage means the
macro-diversity is achieved. The cells avoid *inter symbol interference (ISI)* by using the cyclic prefix [25]. UE is not usually aware about how many cells are used for the signal transmission. Figure no. 14 gives an insight to an eMBMS service area in LTE.

An MBMS service area usually consists of eNodeBs and MBSFN areas. The eNodeBs are synchronized and are responsible for the transmission. An eNodeB usually belongs to a single MBSFN area on a defined frequency channel [25]. Several cells jointly make the MBSFN area and the cells coordinate each other for the MBSFN transmission. However, there might be some cells which are reserved and do not contribute to the transmission. Those can be used for other services at low power [25]. This cell reservation scenario can be compared to NCT-DSFN. The figure illustrates the logic architecture of eMBMS.
In the logical architecture of the eMBMS, a new logical node has been introduced called Multi-Cell/Multicast coordination entity (MCE). This node is responsible for all the MBMS content and resource management as well as for the coordination of the multiple cells transmission in an MBSFN area. The MBMS gateway (MBMS-GW), a logical entity which resides between broadcast/multicast service center (BMSC) and eNodeB (eNB), broadcasts the MBMS data to the each of the eNodeBs which transmit services [26]. The other functions of MBMS-GW include the forwarding MBMS data using the IP multicast and the session start/stop signaling [26]. Then the architecture has three interfaces M1, M2 and M3. M2 and M3 are for the control plane, and M1 is for the user plane. However, the M3 interface can be eliminated by integrating MCE with eNodeB [25]. This leaves two deployment scenarios for eMBMS. Figure no. 16 shows this deployment variation, the right side of the figure depicts the scenario where MCE is included inside the eNodeB and the left side shows the case where MCS is used as a separate node. The MBMS packet delivery is conducted by using IP multicast for the point-to-multipoint case in the M1 interface [25], [26].
2.14 Packet and Resource Plan Scheduling

Packet and resource plan scheduling (PARPS) was introduced to provide a single algorithm for dynamic radio resource management (RRM) [27]. One application of PARPS is DSFN, managing SFN formations is important. This concept affords the dynamic RRM for each data packet without calculating the single-to-interference ratio for every individual packet [27]. In PARPS, a timeslot is provided for each resource plan, a resource plan consists of, for example, transmitter power level, FEC, coding rates and modulation techniques etc [27]. Two algorithms have been proposed namely the optimized and the heuristic algorithm. The optimized algorithm is practical only for computer simulation purposes whereas the heuristic algorithm can be implemented practically i.e. in a real system [27]. PARPS was inspired from the fact that cellular systems would follow asymmetric communication and efficient RRM would be crucial in the downlink. Therefore, PARPS provide a way to form an algorithm which can combine the RRM techniques for dynamic allocation of resource plans as per need. Figure 17 illustrates a simple PARPS example with two transmitters (Tx1, Tx2), four resource plans (R1, R2, R3, R4) and two zones (Z1, Z2) [27].
The above figure shows that during R1, both transmitters send data to zone Z1 and Z2 which suffer high co-channel interference level with the narrow zone. R1 reflects CT-DSFN. In R2 and R3 only one transmitter is allowed to send data giving a rise to the coverage area. R2 and R3 reflect NCT-DSFN. Furthermore, transmitters are said to have formed an SFN, resulting in a bigger zone during R4 which has only Z1 zone.
3 Method

This chapter explains the method of the thesis. All the mathematical formulas required to carry out the work are presented in this chapter.

3.1 Log-distance path loss model

This model is used to measure the distance between transmitter and receiver. The model is usually expressed in dB, hence the name log-normal path loss. However, in this thesis, the simplified form of the model has been studied i.e. the distance is measured in the normal distance unit. There are many factors which contribute to the distance (d) determination. The transmitter power, receive power, antenna gain, fading are few of them. Typically in a cellular system, there are many transmitters which transmit signals for receivers to receive. The receiver might reside near to the transmitters or can be out of the transmitters’ reach. Moreover, the power in watt received at position j from transmitter i is modeled by the following formula:

\[ P_{t,j} = \frac{P_i \cdot F_{i,j} \cdot G_{i,j}}{d_{i,j}^{\alpha}} \quad \ldots \ldots \ (3.1) \]

Here,

- \( i,j \) = transmitter number and receiver position respectively
- \( P_{t,j} \) = Power received at receiver position j from transmitter number i
- \( d_{i,j} \) = distance between receiver position at j and transmitter number i
- \( P_i \) = Transmitter power at \( i^{th} \) position. This is assumed to be 1
- \( F_{i,j} \) = Fading effect between transmitter number i and receiver position j. Antenna heights, antenna gain and carrier frequency determine this factor. In the real world phenomena this is assumed as average 0 dB in log-normal distribution. Standard deviation (δ) taken as 0 dB for non-fading model and 8 dB for fading model. \( F \) is calculated as the value of \( 10^{\delta/10} \).
- \( G_{i,j} \) = Gain between transmitter number i and receiver position j. This is also assumed to be less than 1 in the real world phenomenon
- \( \alpha \) = Propagation path loss constant. The value of \( \alpha \) varies from 2 to 4.

3.2 MFN cell radius calculation

Typically in MFN, there is no interference from other transmitters as they are operating on different frequencies. Therefore, it depends only on the receiver power and the external noise level. To determine the cell radius of the MFN transmitters or the coverage, the following formula is used:

\[ \Gamma = \frac{P_{t,j}}{N} \quad \ldots \ldots \ (3.2) \]
Here, $\Gamma = \text{Signal to interference noise ratio}$

$N = \text{Noise level. This might include interference from external sources outside of the MFN system. This is measured in watt}$

$R_{\text{MFN}} = \text{Transmitter cell radius or cell coverage}$

**Example 1:**
Assume that in a cellular system the external noise is $0.06 \mu W$, required signal to interference noise ratio $\Gamma_0$ 10, Gain $G_{i,j}$ $5 \times 10^{-4}$, standard deviation $\delta$ 0 dB and propagation path loss constant 4. Then the MFN cell radius can be calculated by using Equation no. 3.3 which follows as:

$$R_{\text{MFN}} = \left( \frac{P_i \cdot F_{i,j} \cdot G_{i,j}}{N \cdot \Gamma_0} \right)^{1/\alpha}$$

First the unknown parameter $F_{i,j}$ is to be calculated, $\Gamma_0$ is the required signal to noise ratio, $P_i$ is assumed to be 1. $F_{i,j}$ is calculated by using the following formula:

$F_{i,j} = 10^{6/10}$

$F_{i,j} = 10^{0/10}$

$F_{i,j} = 1$

Hence, the MFN radius is calculated as follows:

$$R_{\text{MFN}} = \left( \frac{1.1 \cdot 5 \cdot 10^{-4}}{6 \cdot 10^{-8}} \right)^{1/4} \text{ distance units}$$

$$R_{\text{MFN}} = 5.37 \text{ distance units}$$

This radius has been used for the scheme-A, scheme-B and scheme-C cell radius in chapter 4 (section 4.1) for the MFN schemes. This radius has been chosen for illustration purpose.

**3.3 SFN cell radius calculation**

In SFN, there might be interferences from other nearby SFNs and the cell radius depends on the interfering receiver power, receiver power and the external noise level. The formula is used to determine the cell radius in SFN.

$$\Gamma = \frac{\sum_{i \in \text{SFN}} P_{i,j}}{\sum_{i \in \text{SFN}} P_{i,j} + N} \ldots \ldots (3.4)$$
\[
\Gamma = \frac{P_i \cdot F_{i,j} \cdot G_{i,j}}{\sum_{i \in \text{SFN}} P_{i,j} + n_0} \quad \text{substituting } P_{i,j} \text{ from Eq. (3.1)}
\]

\[
d_{i,j} = \left( \frac{P_i \cdot F_{i,j} \cdot G_{i,j}}{(\sum_{i \in \text{SFN}} P_{i,j} + n_0) \cdot \Gamma} \right)^{1/\alpha}
\]

\[
R_{\text{SFN}} = \left( \frac{P_i \cdot F_{i,j} \cdot G_{i,j}}{(\sum_{i \in \text{SFN}} P_{i,j} + n_0) \cdot \Gamma} \right)^{1/\alpha} \quad \text{here } R_{\text{SFN}} = d_{i,j} = \text{Cell radius} \quad \ldots \ldots \text{(3.5)}
\]

Here,
\[\sum_{i \in \text{SFN}} P_{i,j} = \text{Power received by the receiver from the set of transmitters belong to the SFN}\]
\[\sum_{i \in \text{SFN}} P_{i,j} = \text{Power received by the receiver from transmitters outside of the SFN i.e. the interference power}\]
\[R_{\text{SFN}} = \text{SFN Cell radius}\]

**Example 2:**

Assume that in a cellular system the external noise is 0.06 µW, required signal to interference noise ratio \(\Gamma_0 10\), Gain \(G_{i,j} \ \ \ \ \ \ \ 5 \times 10^{-4}\), interference power \(2 \times 10^{-9}\) W, standard deviation \(\sigma 0\) dB, and propagation path loss constant \(4\). Then the cell radius can be calculated using Equation no. 3.5 which is shown below:

\[
R_{\text{SFN}} = \left( \frac{P_i \cdot F_{i,j} \cdot G_{i,j}}{(\sum_{i \in \text{SFN}} P_{i,j} + N) \cdot \Gamma_0} \right)^{1/\alpha}
\]

Here, first \(F_{i,j}\) needs to be calculated, \(\Gamma_0\) is the required signal to noise ratio, \(P_i\) is assumed to be 1. \(F_{i,j}\) is calculated by using following formula:

\[
F_{i,j} = 10^{(0/10)}
\]

\[
F_{i,j} = 10^{(0/10)}
\]

\[
F_{i,j} = 1
\]

Hence, the SFN radius is

\[
R_{\text{SFN}} = \left( \frac{1 \cdot 1 \cdot 5 \cdot 10^{-4}}{(6 \cdot 10^{-8} + 2 \cdot 10^{-9}) \cdot 10} \right)^{1/4} \text{ distance units}
\]

\[
R_{\text{SFN}} = 12.42 \text{ distance units}
\]

**3.4 SFN Formation**

In this section, SFN formation is discussed and shown by means of figures. First section corresponds to the SFN formation with interference and the following section refers to the SFN formation without any interference.
3.4.1 SFN with interference (continuous transmission)

In SFN, transmitters are affected by co-channel interference as all the transmitters are transmitting using the same frequency. This resembles the continuous transmission cases of SFN. There is also interference from transmitters that do not belong to the SFN. As equation no. 3.5 reflects the cell radius calculation of SFN, so equation no. 3.5 is used to demonstrate the following SFN illustrations.
There are total of 4 transmitters (Tx). On the top image of figure 18, the SFN size is 1 meaning that 3 others transmitters are interfering the single SFN transmitter. Clearly this SFN has a very low coverage due to the interference. SFN size 2 has a better coverage as only two transmitters cause interference this SFN formation. The last image has an SFN size of 3 which understandably has the best coverage since only one transmitter causes interference.

3.4.2 SFN with no interference (non-continuous transmission)

The next figures demonstrate SFNs with no interference; this is the not-continuous transmission case. For this illustration Equation 3.5 has been modified. As no interference is taken into account, therefore the modified equation becomes:

\[ R_{\text{SFN}} = \left( \frac{P_i \cdot F_{ij} \cdot G_{ij}}{n_0 \star \Gamma} \right)^{1/\alpha} \quad ... ... (3.6) \]

The equation seems to be similar to the equation no. 3.3, however, number of receivers equals to the total number of receivers in the SFN.
For the same SFN sequence, a rapid increase in the coverage is seen with no interference. This demonstrates how much coverage is affected due to the interference. Moreover, SFN of size 4 would, understandably, increase the coverage area. This is shown in the figure.
3.5 Channel Utilization Calculation

Channel utilization usually refers to how efficiently the channel and transmitter are utilized to transfer the program over that given channel. This is basically calculated as number of programs covered divided by the multiplication of the channel and the transmitter required. Therefore, the channel utilization can be calculated as follows:

$$\eta = \frac{N_{pro\_cov}}{N_{Tx\_util} \cdot N_{Ch}} \ldots (3.7)$$

Here, $\eta$ is the channel utilization, $N_{pro\_cov}$ is the total number of programs being covered by each scheme in the coverage area, $N_{Tx\_util}$ is total number of transmitters being used and $N_{Ch}$ is the total number of channels required for transmitting those covered programs.

Now in order to define the MSSE, we need to define the multiuser channel utilization first. And for this the above formula (3.7) is used but instead of number of programs covered ($N_{pro\_cov}$) number of covered receivers is used ($C_{Rx}$). The formula becomes,

$$\eta_M = \frac{C_{Rx}}{N_{Tx\_util} \cdot N_{Ch}} \ldots (3.8)$$

3.6 System Spectral Efficiency Calculation

System spectral efficiency (SSE) refers how efficiently information is transferred over a given bandwidth using the channel utilization. This is basically calculated as the multiplication of channel capacity and channel utilization, and then divided by the given bandwidth. SSE is expressed as (bit/s)/Hz per site. The formula shows the calculation:

$$S = \eta \cdot \frac{R_{Ch}}{B_{Ch}} \ldots (3.9)$$

Here, $S$ = System spectral efficiency  
$R_{Ch} = B_{Ch} \cdot \log_2(1+SINR)$ [Shannon-Hartley Theorem]  
$B_{Ch}$ = Channel Bandwidth  
$\eta$ = Channel utilization

As stated earlier that a new measure would be defined i.e. multiuser system spectral efficiency (MSSE). For this new definition, channel utilization is replaced by multiuser channel utilization in the above formula (3.9). The formula becomes:

$$S_M = \frac{\eta_M \cdot R_{Ch}}{B_{Ch}} \ldots (3.10)$$
4 Simple Model

This chapter discusses the simple model where seven schemes being designed and analyzed in this thesis work. The first section corresponds to the implementation of the schemes without fading. The following section portrays the schemes’ evaluation. For this simple model approach, fixed receiver positions have been used.

For designing the case studies i.e. the schemes, a few assumptions have been considered. There will be a total of four transmitters ($T_x$), each transmitter has the privilege to operate on multiple channels. The receivers that are out of the coverage cannot receive any signal from any of the transmitters. To increase the coverage and make the outage receivers to receive the signal, SFN will be formed. Later on, a variant of SFN, namely DSFN, will be studied which allows to switch between SFN formations in different timeslots. The following acronyms and assumptions have been made for the case studies’ evaluation.

\[ N_{Tx} = \text{Number of transmitters (4)} \]
\[ N_{Rx} = \text{Number of receivers (9)} \]
\[ N_{Ch} = \text{Number of Channels (varies)} \]
\[ C_{Rx} = \text{Covered receivers (varies for SFN and MFN)} \]
\[ N_{pr} = \text{Total number of TV programs (6)} \]
\[ N_{prj} = \text{Number of programs requested within a single SFN or cell j} \]
\[ N_{pr} = \text{Number of programs offered in the SFN} \]

4.1 Performance measurement of case studies (without Fading)

This section corresponds to the implementation of the seven schemes without fading. The following illustrations have been evaluated with the fixed receiver positions.

4.1.1 Scheme A: Unicasting over MFN

This scheme, unicasting over MFN, is a point-to-point service. Example applications for this scheme are traditional TV over cell phone, YouTube, internet TV etc. This scheme requires that every transmitter operates on a different frequency. Furthermore, each receiver requires a unique channel. This scheme makes use of four transmitters where each transmitter is eligible to transmit all the TV programs in its specified time domain. For illustration, only 7 receivers out of 9 receivers can receive TV program signal (see figure 21). This yields coverage probability ($C_p$) of 77.78%. Mathematically it is shown below.

\[ C_p = \frac{C_{Rx}}{N_{Rx}} \quad (4.1) \]
\[ C_p \% = \frac{7}{9} \cdot 100 \% \]
\[ C_p \% = \text{77.78\%}. \]

Rx5 and Rx8 are in the outage state. As Rx5 is intended for program 5, this scheme cannot cover program 5. As MFN is utilized for this scheme, it only suffers from external noise. The coverage probability is low. Since each receiver requires a unique channel in unicasting, hence the total number of channels required equal to total number of covered receivers in the coverage area. Therefore, the total number of channel in this scheme is as follows:

\[ N_{\text{Ch}} = C_{\text{Rx}} \quad (4.2) \]
\[ N_{\text{Ch}} = 7 \]

A total of 7 channels are required for scheme A. Channel utilization and multiuser channel utilization becomes 0.17857 and 0.25 respectively. The following figure illustrates an insight of the scheme.

Figure 21 Scheme A: Unicasting over MFN
4.1.2 Scheme B: Broadcasting over MFN

Scheme B is broadcasting over MFN. Traditional TV and DVB-T over MFN are prime examples for this scheme. This means that each transmitter transmits all the TV programs, however, it does not require a unique channel for each receiver. It requires separate channel for each TV program. Each transmitter requires channels equal to the number of TV programs available for broadcasting. Therefore, channels required by this scheme can be calculated from the following equation.

\[
N_{Ch} = N_{Tx} \cdot N_{pro} \quad (4.3)
\]

\[
N_{Ch} = 4 \cdot 6
\]

\[
N_{Ch} = 24
\]

A total of 24 channels required for broadcasting over MFN. Some receivers reside near the transmitter border but cannot receive any signal and are in the outage state. 2 out of 9 receivers are in the outage state, and program 5 remains unreachable. Therefore, like in scheme A, this scheme has a low coverage probability of 77.78%. As the number of channels requirement is very high in this scheme, and has the lowest transmitter utilization. Channel utilization and multiuser channel utilization become 0.052083 and 1.0417 respectively. The following figure illustrates scheme B.
4.1.3 Scheme C: IP Multicasting over MFN

This, IP Multicasting over MFN, scheme follows the idea that of a point-to-multipoint service. MBMS/eMBMS, when MFN is used, tends to follow the idea of this scheme. Each transmitter transmits only those TV programs for which it has receiver inside the coverage area. For illustration, in figure 23, Tx2 and Tx3, each has only single receiver, Tx4 has receivers from 3 TV programs, and Tx1 has two receivers of different TV programs. Therefore, the transmitters would only transmit those TV programs. Moreover, for this scheme, number of channels would equal the aggregated TV programs in the MFN. Mathematically, the relation is as follows.

\[
N_{Ch} = \sum_{\pi=1}^{N_{Tx}} N_{Prj} \quad (4.4)
\]

For the particular example as shown in the illustration, a total number of channels would be:

\[
N_{Ch} = 2 + 1 + 1 + 3 = 7
\]

This number is much lower compared to scheme B. Approximately 243% reduction is achieved by this scheme from scheme B in terms of channel requirement for this particular illustration. However, this scheme does not increase the coverage area. The coverage probability remains 77.78 % as was the case in both scheme A and scheme B, since 7 receivers are covered by this scheme out of total 9 receivers. Moreover, program 5 still remains outside of the coverage. Channel utilization and multiuser channel utilization becomes 0.17857 and 2.7778 respectively. Compared to scheme A, this scheme does not have any increase in channel utilization percentage. However compared to scheme B, channel utilization is increased by approximately 243% and the multiuser channel utilization gain is around 166%. Figure 23 demonstrates this scheme.
4.1.4 Scheme D: Broadcasting over SFN

Broadcasting over SFN implies that each transmitter transmits the same signal over the same frequency at the same time. DVB-T over SFN can be compared with the idea of this scheme. Same frequency is utilized by all transmitters and all transmitters are grouped together to make the SFN in this particular scheme. Therefore, this scheme does not suffer from any kind of interference from other transmitters inside the system. As a result, the coverage area is increased and all those receivers that were in outage state in the previous schemes have been covered along with program 5. Therefore, the coverage probability (Cp) rises to 100% in broadcasting over SFN. Cp is increased by approximately 28% compared to previous schemes. As for channel requirement, the number of TV programs would be the number of channels required. This signifies that the transmitters would behave as if they were a single transmitter and would broadcast only the number of programs required to be transmitted in the region. The mathematical formula for calculating the channel requirement is:

\[ N_{Ch} = N_{pro} \quad (4.5) \]
Hence, the channel requirement by this scheme drops off about 300% from scheme B and approximately 17% from scheme A and scheme C. Significant reduction compared to the previous schemes. Therefore, channel utilization is also increased to 0.25; in terms of percentage this is increased by approximately 380% compared to scheme B. Multiuser channel utilization is increased by 300%. The following figure illustrates broadcasting over SFN.

**4.1.5 Scheme E: IP Multicasting over CT-DSFN**

*IP multicasting over CT-DSFN* reflects a continuous transmission dynamic SFN (CT-DSFN). The idea of this scheme is new, and some proposed applications of this scheme include DVB-T, eMBMS. In this scheme, the term dynamic implies that the transmitters would be grouped together to form zones and this zone formation changes according to the need in different timeslots. Continuous transmission reflects the fact that each zone would be transmitting continuously at full transmitter power. In the illustration given below, a total of possible 15 combinations have been...
shown for the system consisting of 4 transmitters. Each combination is called a resource plan. This resource plan can be changed in different timeslots as per need. The coverage probability, and number of channels requirement changes for each resource plan. In the example shown in figure 25, the coverage probability ranges from 44.44% to 100%. The channel requirement, for the individual resource plans not for the overall scheme, ranges from 1 to 6. In the first resource plan, each zone suffers from co-channel interference from the other zones, hence the coverage probability is very low (44.44%). Each zone is represented by different color. However, the number of channel required is also very low for this particular resource plan, only one channel is required for transmission. In the last resource plan where all the transmitters have formed a single SFN, the coverage probability increases to 100% as no transmitter suffers from co-channel interference. However, the channel requirement is also high (6). Therefore, the idea is to utilize different resource plans in different timeslots in order to minimize the channel requirements which will provide spectrum efficiency. To materialize this resource plan to timeslot assignment, the PARPS algorithm is to be utilized. In PARPS, the resource plan to timeslot assignment can be defined according to:

\[
A_{R2T} = \begin{cases} 
    r, & \text{if resource plan } r \text{ is assigned to timeslot } t \\
    0, & \text{otherwise}
\end{cases} \quad (4.6)
\]

Programs arrive in the queue of the centralized system. A program can be placed into the queues of several alternative resource plans, one zone for each program, but it is removed from all queues when it is sent, according to the deployed PARPS scheduling algorithm. A certain program \( p \) is placed into the queue of one of the zone \( z \) of resource plan \( r \), if the maximum numbers of the receivers that are watching that program (and have joined that multicast group) are covered by that zone. The PARPS scheduling algorithm assigns a resource plan to each timeslot, and assigns programs to timeslots and zones. The scheduling algorithm implies that the system can send most packets in the next time slot. Each packet corresponds to a single program of the queue i.e. for this scheme a single zone. The algorithm will choose the resource plan with most number of zones that cover programs in the queue. This way the algorithm chooses the best resource plan for each time slot. The following queue formations show some of the best resource plans that can be used for this example.

<table>
<thead>
<tr>
<th>Resource plan 2</th>
<th>Resource plan 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone1</td>
<td>Zone1</td>
</tr>
<tr>
<td>Zone2</td>
<td>Zone2</td>
</tr>
<tr>
<td>Zone3</td>
<td>Zone3</td>
</tr>
<tr>
<td></td>
<td>( P3 \mid P6 )</td>
</tr>
<tr>
<td></td>
<td>( P1 \mid P4 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource plan 9</th>
<th>Resource plan 11</th>
</tr>
</thead>
</table>
This can be represented by the following three-dimensional queue matrix $Queue$:

$$Queue_{z,p,r} = \begin{cases} 1, & \text{if program p is placed in the queue of zone z of resource plan r} \\ 0, & \text{otherwise} \end{cases} \quad (4.7)$$

In the example above, the queue matrix for resource plan, $r=9$, is represented as follows:

$$Queue_{z,p,9} = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (4.8)$$

From the above queues, it is clear that resource plan 9 is the most efficient as it can send two different programs in each timeslot. Moreover, program 2 and 5 can only be sent using resource plan 15. Therefore, for this particular illustration, resource plan 9 and resource plan 15 have been utilized in 4 different timeslots (see Eq. 4.9). In plan 9, there are two zones each operating using two transmitters. In zone1, there are two programs (program 3 and program 6) and 3 receivers (Rx3, Rx6 and Rx9). Zone2 also has two programs (program 1 and program 4) and 3 receivers (Rx1, Rx4 and Rx7). Rx8 and Rx9 can only be captured in plan 15. Hence, this plan 15 requires to be used. Plan 15 can capture all the receivers, however, this plan is used only to transmit program 2 and program 5 in two timeslots by utilizing single channel. Plan 9 transmits other four programs by utilizing two timeslots. Hence, four timeslots would be needed. Each timeslot would only require a single channel.

For this example, the assignment matrix schedule for resource plan to timeslot is shown below:

$$A_{R2T} = (9,9,15,15) \quad (4.9)$$

During timeslot, $t=1$, plan 9 is used and one channel is utilized for program 3 in zone1. This channel is reused in zone2 for program 1. During $t=2$, plan 9 is utilized again and a single channel is required for program 6, and program 4 in zone1 and zone2 respectively. During $t=3$, resource plan 15 is employed to transmit program 2. During $t=4$, plan 15 transmits program 5.
The assignment matrix of program to timeslot is defined as:

\[ A_{P2T_{lp}} = \begin{cases} 
1, & \text{if program } p \text{ is assigned to timeslot } t \\
0, & \text{otherwise} 
\end{cases} \]  

(4.10)

Hence, the program to timeslot schedule for this example becomes:

\[ A_{P2T} = \begin{pmatrix} 
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 
\end{pmatrix} \]  

(4.11)

Now the program to timeslot and zone assignment matrix is defined as:

\[ A_{P2TZ} = \begin{cases} 
p, & \text{if program } p \text{ is assigned to timeslot } t \text{ and zone } z \\
0, & \text{otherwise} 
\end{cases} \]  

(4.12)

For the example shown in figure 25, the corresponding schedule would become as follows:

\[ A_{P2TZ} = \begin{pmatrix} 
3 & 6 & 2 & 5 \\
1 & 4 & 0 & 0 
\end{pmatrix} \]

(4.13)

The overall transmission for this scheme is shown in figure no. 26. The coverage probability is 100% since all the receivers are covered. Since only one channel is required for this scheme in each timeslot, hence, total number of channels required becomes 4. Furthermore, the number of channel required reduced to approximately: 83% compared to scheme B, 43% compared to scheme A, scheme C, and 33% compared to scheme D for this particular example. The number of channel required can be calculated mathematically as:

\[ N_{Ch} = T \]  

(4.14)

T is the total number of timeslots required for the overall transmission of this scheme. Hence, the channel utilization for this scheme is 0.375. Significant increase compared to previous schemes. Compared to scheme B, the channel utilization is increased by approximately 620%, and compared to scheme D, the increase is approximately 50%. As for multiuser channel utilization case, the gain is roughly 500% from scheme B and 50% from scheme D.
Figure 25 Scheme E: IP Multicasting over CT-DSFN
4.1.6 Scheme F: IP Multicasting over NON-SFN DCA

This scheme can be compared to eMBMS over SFN. This scheme corresponds to the fact that there will be no SFN; meaning the transmitter grouping is not utilized. Maximum one transmitter is used in each zone. For example with 4 transmitters, 15 possible combinations are possible (see figure 27). In this scheme, some transmitters can be switched off in some resource plans. This scheme can also adopt different resource plans in different timeslots. The coverage probability, and number of channel required will be different in alternative resource plans. For the example shown in figure 27, the coverage probability ranges from 11.11% to 77.78%. Number of channels required varies from 1 to 3. These calculations are only for the individual resource plan; the overall scheme’s calculations would be different. Alternative resource plans will be used in different timeslots as was the case in scheme E. The PARPS algorithm will be used for the resource plan to timeslot assignment. Eq. 4.6 defines the resource plan to timeslot assignment. Programs arrive in the queue of the centralized system. In contrast to scheme E, where a zone was sufficient for a program, in this scheme a zone might not suffice for a program. More than one zone might be required for a single program. Therefore, it is likely that a program might require more than a single timeslot. Furthermore, it is possible that a program might not be covered by any of the resource plans. A program is placed into the queue of a resource plan if zone(s) of that resource plan cover the maximum number of

![Figure 26 Overall Scheme E transmission](attachment://figure26.png)
receivers that are watching that program (and have joined that multicast group). The Program is removed from the queue when it is sent. The PARPS scheduling algorithm assigns a resource plan to each timeslot, and assigns programs to timeslots and zones. The scheduling algorithm implies that the system can send most packets in the next time slot. As each packet corresponds to a single program of the queue, for this scheme more than one zone might be needed for a packet. The algorithm will choose the resource plan with most number of zones that can cover programs of the queue. Thus the best resource plan is used in each timeslot. Some of the best resource plans are shown in queue formations.

<table>
<thead>
<tr>
<th>Resource plan 1</th>
<th>Resource plan 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone1</td>
<td>Zone1</td>
</tr>
<tr>
<td>P1</td>
<td>P1</td>
</tr>
<tr>
<td>Zone2</td>
<td>Zone2</td>
</tr>
<tr>
<td>P4</td>
<td>P4</td>
</tr>
<tr>
<td>Zone3</td>
<td>Zone3</td>
</tr>
<tr>
<td>P1</td>
<td>P4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource plan 8</th>
<th>Resource plan 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone1</td>
<td>Zone1</td>
</tr>
<tr>
<td>P6</td>
<td>P3</td>
</tr>
<tr>
<td>Zone2</td>
<td>Zone2</td>
</tr>
<tr>
<td>P4</td>
<td>P3</td>
</tr>
<tr>
<td>Zone3</td>
<td>Zone3</td>
</tr>
<tr>
<td>P4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource plan 13</th>
<th>Resource plan 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone1</td>
<td>Zone1</td>
</tr>
<tr>
<td>P6</td>
<td>P3</td>
</tr>
<tr>
<td>Zone2</td>
<td>Zone2</td>
</tr>
<tr>
<td>P1</td>
<td>P3</td>
</tr>
<tr>
<td>Zone3</td>
<td>Zone3</td>
</tr>
<tr>
<td>P1</td>
<td>P2</td>
</tr>
<tr>
<td>Zone4</td>
<td>Zone4</td>
</tr>
<tr>
<td>P1</td>
<td></td>
</tr>
</tbody>
</table>

The queue formation is defined in Eq. 4.7. In the example above, the queue matrix for resource plan, \( r=15 \), is represented as follows:

\[
Queue_{z,p,15} = \begin{pmatrix}
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]  \hspace{1cm} (4.15)

As the maximum number of packets is to be sent using the PARPS algorithm, and each packet corresponds to zone(s) that cover the program, so resource plan 15 is the best resource plan for this scheme as two programs can be sent. By utilizing this resource plan program 1 and program 3 can be sent during timeslot \( t=1 \). Another consideration for this scheme is to utilize the least number of transmitters whenever possible as transmitters can be shut off in alternative resource plans. Therefore, during timeslot \( t=2 \), program 2 and program 6 can be sent by the resource plan 8 by using only 2 transmitters although resource plans 12, 13, and 15 also could have been used to transmit these two programs. These resource plans require more
transmitters, hence, not considered. Program 4 can be transmitted using resource plan 1 during timeslot t=3. Program 5 is not covered by any of the resource plans; consequently this scheme cannot transmit this program. The resource plan to timeslot assignment for this example becomes:

\[ A_{R2T} = (15,8,1) \]  
(4.16)

The program to timeslot assignment is defined in Eq. 4.10. The schedule for this example corresponds to:

\[ A_{P2T} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \]  
(4.17)

Now the program to timeslot and zone assignment schedule, which is defined in Eq. 4.12, would become:

\[ A_{P2TZ} = \begin{pmatrix} 3 & 6 & 4 \\ 3 & 2 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \text{zone}1 \\ \text{zone}2 \\ \text{zone}3 \\ \text{zone}4 \end{pmatrix} \]  
(4.18)

There are total of 3 timeslots which means, 3 channels required by this scheme according to Eq. 4.14. Channel utilization becomes 0.7143- which is the best among the schemes, however, the drawback is that it cannot transmit program 5 and the coverage probability is also on the lower side. Channel utilization is increased by approximately 1271% and 186% compared to scheme B and scheme D respectively. For multiuser channel utilization the gain is around 966% and 166% from scheme B and D respectively. Figure no. 28 shows the overall transmission for this scheme. The coverage probability is 77.78%.
Figure 27 Scheme F: IP Multicasting over NON-SFN DCA
4.1.7 Scheme G: IP Multicasting over NCT-DSFN

IP Multicasting over NCT-DSFN makes use of non-continuous transmission dynamic SFN (NCT-DSFN). This scheme can be described as a union of scheme E and scheme F. Non-continuous transmission means that some transmitters are switched off in some resource plans. This scheme can offer a total of 51 possible resource plans as shown in figure no. 29. The coverage probability ranges from 11.11% to 100% and the numbers of channels require ranges from 1 to 6 for this example. Like in scheme E, this scheme can also adopt different resource plans in different timeslots. PARPS facilitates to schedule the assignment of resource plans in different timeslots. The resource plan to timeslot assignment definition is the same as defined in Eq. 4.6. Programs arrive in the queue of the centralized system, and queue formations are formed in the similar manner as described in scheme E (defined in Eq. 4.7). Queue formations for some of the best resource plans for this scheme are shown below.

<table>
<thead>
<tr>
<th>Resource plan 4</th>
<th>Resource plan 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone1</td>
<td>Zone1</td>
</tr>
<tr>
<td>Zone2</td>
<td>Zone2</td>
</tr>
<tr>
<td>P6</td>
<td>P3 P6</td>
</tr>
</tbody>
</table>

Figure 28 Overall Scheme F transmission
In the example above, the queue matrix for resource plan, \( r=8 \), is represented as follows:

\[
Queue_{z,p,8} = \begin{pmatrix}
0 & 0 & 1 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
\]  

(4.19)

The PARPS scheduling algorithm that is being used implies that most packets are transmitted in next timeslot from these queues. Each packet corresponds to a single zone of the queue as a program can be covered by a single zone in this scheme. The algorithm will choose the resource plan with most number of zones that cover programs in the queue. As NCT-DSFN implies that the transmitters can be switched off during some resource plans, in this scheme a resource plan will be chosen for a timeslot which can send most packets by utilizing minimum number of transmitters. From the queues, it is seen that no resource plan can send more than 2 programs per timeslot, and alternative resource plans can send same program combinations in the same timeslot. For example, program 4 and program 6 can be sent by alternative
resource plans in the same timeslot. However, resource plan 19 can send program 4 and 6 by using only 2 transmitters. Hence, this resource plan is used during timeslot, t=1. Now the resource plan 33 can also send 2 programs in a single timeslot. Program 1 and program 3 can be sent by using this resource plan. It is noteworthy that this resource plan can also send program 4 and 6, however, requires 4 transmitters. Hence, this resource plan is only used for program 1 and program 3 during timeslot, t=2. More than one resource plan can send program 5 and program 2, but resource plan 41 and 44 can send these programs by employing 3 transmitters. Therefore, these 2 resource plans are used during timeslot, t=3 and t=4 respectively.

Here, the assignment matrix resource plan to timeslot schedule is shown for this scheme:

\[ A_{RT} = (19,33,41,44) \]  

(4.20)

The program to timeslot assignment is defined in Eq. 4.10. The schedule for this example corresponds to:

\[
A_{P^2T} = \begin{pmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0
\end{pmatrix}
\]  

(4.21)

Now the program to timeslot and zone assignment schedule, which is defined in Eq. 4.12, would become:

\[
A_{P^2TZ} = \begin{pmatrix}
6 & 3 & 5 & 2 \\
4 & 1 & 0 & 0
\end{pmatrix}
\]  

\( \text{zone1} \)  

(4.22)

Similar to scheme E, this scheme requires a total of 4 channels as it has four timeslots. The algebraic formula for the channel requirement calculation is same as shown in Eq. 4.14. Although this scheme requires 4 channels like scheme B, but the average transmitter employed is low compared to scheme E. Hence, the channel utilization is .05 which offers an increase by approximately 860%, 100%, and 33.33% compared to scheme B, D, and E respectively. Moreover, multiuser channel utilization offers gain roughly 700%, 100% and 33% respectively from scheme B, D and E. Therefore, if both coverage probability and transmitter utilization are considered then this scheme yields the best performance. Overall transmission for this scheme is shown in figure no. 30. The coverage probability is 100% since no receiver is in outage state.
Figure 29 Scheme G: IP Multicasting over NCT-DSFN
4.2 Case Studies Evaluation

In this section, the evaluations of the case studies have been presented in the form of coverage probability and number of channels require.

4.2.1 Coverage Probability

The following figure (figure no. 31) demonstrates the coverage probability evaluation of the schemes. Scheme D, E and G have approximately 28% improvement of coverage probability from the MFN schemes. Scheme F uses the single frequency but does not take advantage of transmitter grouping, hence behaves as non-SFN. Because of this non-SFN nature, scheme F has the coverage probability similar to the MFN schemes.
4.2.2 Channel Utilization Evaluation

Figure no. 32 illustrates the channel utilization evaluation for each scheme. It is seen that scheme B is the most inefficient scheme. Scheme G offers gain of around 180%, 860%, 180%, 100%, and 33% from scheme A, B, C, D and E respectively. Scheme E, F and G are better than scheme D in terms of channel utilization. Although scheme E and G require same number of channel, scheme G utilizes less number of transmitters- therefore, scheme G provides better channel utilization. Also, scheme F has better channel utilization gain –but it also has a low coverage probability- hence it is predicted to provide less gain in random cases. Figure no. 33 shows the multiuser channel utilization by each scheme. From the figure it is seen that scheme A seems to be the most inefficient scheme. All the SFN schemes provide better performance than the MFN schemes. Although scheme F is the best in terms of multiuser channel utilization- but this scheme offers low coverage probability- therefore scheme G is the best scheme. Hence, it is predicted that scheme G would provide better system spectral efficiency. This is discussed in chapter 6 for the all the random cases.
Figure 32 Channel Utilization (Simple Case)

Figure 33 Multiuser Channel Utilization (Simple Case)
5 Random Model

This chapter illustrates all the seven schemes that were designed in the previous chapter for random cases. Two random cases will be studied i.e. homogeneous case and heterogeneous case. The programs will be distributed among the receivers using the zipf-law.

The following parameters will be used for random cases evaluation:

- $N_{tx}$ = Number of transmitters (4)
- $N_{rx}$ = Number of receivers (100)
- $N_{ch}$ = Number of Channels (varies)
- $C_{ax}$ = Covered receivers (varies for SFN and MFN)
- $N_{pro}$ = Total number of TV programs (30)
- $N_{pr}$ = Number of programs requested within a single SFN or cell j
- $N_{n}$ = Number of programs offered in the SFN

Coverage probability calculation, number of channel required calculation and packet scheduling for scheme E, F and G are same as described in the simple model, hence these are not discussed in this chapter. The program selection model i.e. zipf-law is described in the first section.

5.1 Zipf-Law

Zipf law is a scientific law which has been derived from the family of power law probability distributions [28]. This refers to the fact that by using this law, mathematical statistical operations can be made on many types of data studied in physical or social sciences [28]. This law states that, for example, if the popularity of a program for TV is considered, then the most popular program’s frequency would be approximately inversely proportional to its rank in the table of frequency. Thus the most popular program would be viewed twice as that of the second most popular program, thrice that of the third most popular program and likewise. This law can be very useful for some scientific research areas as researchers can use this zipfian distribution to evaluate their research ideas. Moreover, in this work, this law has been used for distributing programs selection to the receivers. The following formula would provide an idea about how this law works. The frequency of a program is determined as [28],

$$f_{\text{program}} = \frac{1/r_{pro}^\theta}{\sum_{n=1}^{N_{pro}} 1/n^\theta}$$ ...

Here,

- $N_{pro}$ = total number of programs,
- $r_{pro}$ = rank of the program and
- $\theta$ = exponent value of characterizing distribution
The value of $\theta$ varies, however, it usually remains between 0.5 and 1 according to some research papers [34, 35, and 36]. For this thesis work, the value has been chosen as 0.95. In [37], the author had used the $\theta$ value as 0.95 where the work was carried on “On Synchronization Frames for Channel Switching in a GOP-Based IPTV Environment”. Therefore, this value has been chosen for this thesis work as the work is in similar area. However, in this case the law does not behave exactly like zipf-law, exactly for zipf-law behavior $\theta$ should be 1. The law is called zipf-like distribution if the value of $\theta$ is other than 1.

The following figure shows a logarithmic plot of this law. The X-axis is for the rank of the program i.e. $r_{pro}$. It has been evaluated for $\theta$ values between 0.65 and 1, 10 programs and 30 receivers.

Now the three random cases are presented in the following sections.

5.2 Homogeneous Case

The homogenous case implies that there is only one network. In this case all the transmitters belong to the same network. It is further assumed that program $p$ is $p^{th}$ popular i.e. program 1 is the most popular, program 2 is the second most popular and likewise. The program to receivers’ distribution is same in all the simulations.
That means the program's popularity is unchanged. The following figure shows scheme A for this case. As mentioned previously, the coverage probability and the number of channels requirement calculation are the same as described in the simple model. Here, in the figure single color has been used for the receivers' positions which signify the fact that this is a homogeneous network.

![Scheme A: Unicasting over MFN](image)

For scheme B, C, and F the coverage probability would remain the same as seen in the simple model, these schemes differ only in the number of channels requirement. Therefore, the figures for these schemes are not shown here. The next figure (figure no. 36) shows scheme D of homogenous case which is broadcasting over SFN. The coverage probability is increased from 79% to 96%, an increase about 17%. The coverage probability for the remaining schemes i.e. scheme E and G would not change, the number of channels requirement (number of timeslots) would only change.
5.3 Heterogeneous Case

In this case, the network is divided into two networks, and each network operates by utilizing two transmitters. Unlike homogeneous case, where program p was p-th popular, here, the popularity of the programs is randomized in each network. The idea is that program p might be the most popular in network 1 at certain time of the day while the same program is not that popular in network 2 during that time. Also, there might be a certain time of the day where both networks have the same program as the most popular program. In this way, a better spectral efficiency can be achieved. For all the random cases the same receivers’ positions have been used and the receivers’ position was randomly chosen in each simulation. The figures for this case would be same as was in homogenous case; the results for channel utilization i.e. system spectral efficiency will be different. Hence, only the figure for scheme A is shown in order to distinguish between homogenous and heterogeneous case. In the following figure no. 37, the receivers’ positions have been shown by two different colors where each color represents a different network.
5.4 Fading Model

In the above scenarios, fading was not considered. In this section, the fading model is discussed. As stated in section 3.1, that for the non-fading model the standard deviation (δ) value is considered to be 0 dB and for the fading model the value is considered to be 8 dB. In the non-fading model random cases, it is seen that MFN cell is circle shape, however in the fading model the cell would not be circle shape. The cell border in all the schemes for non-fading model was smooth, however, in fading model it would not be smooth. Moreover, the cell zones did not overlap in the non-fading model, in the fading model the cell zones might overlap. This might result in receiver(s) being covered by more than one zone. In the following figures, fading models for scheme A and scheme D are shown.
Scheme A: Unicasting over MFN

![Figure 38 Unicasting over MFN (Fading)](image)

Scheme D: Broadcasting over SFN

![Figure 39 Broadcasting over SFN (Fading)](image)
From the above figures, it is seen that cell border-edge is not smooth. Scheme A figure shows that receiver(s) near the borders might be covered by more than one zone if the zones overlap.
6 Results

The schemes that have been designed and analyzed are evaluated based on two of the most important aspects of wireless communications namely the coverage probability and system spectral efficiency. In addition, a new definition has been introduced, which is multiuser system spectral efficiency. This new term has also been discussed. Coverage probability is the number of receivers inside the coverage area i.e. not in the outage state. For example, if there are total of 100 receivers and 10 receivers are in the outage state, then the coverage probability would be 90% and the outage probability 10%. System spectral efficiency is calculated based on channel capacity, bandwidth and channel utilization. Mathematical formulas for the above calculations have been shown in chapter 3 and chapter 4.

A total of seven schemes for two random cases have been designed and analyzed. Scheme A, B, and C are based on multi frequency while other schemes take advantage of single frequency. The aim for examining both frequency networks was to analyze and differentiate their performances in terms of coverage probability and spectral efficiency, and to find out the best scheme. All the schemes were initially evaluated without taking fading into consideration and then later fading was added to the schemes. Both homogeneous and heterogeneous channel selection models have been investigated.

The parameters and values that were used to generate the results are presented in table no. 1. The number of transmitters, number of receivers, number of programs, transmitter gain, propagation path loss constant, and external noise values were constant for all the schemes’ evaluation. The SINR value has been taken 10 dB as standard for comparing the coverage probability. However, the SINR value would be changed in order to get the diversity gain of SFN from MFN, therefore, the exact system spectral efficiency will be calculated based on the diversity gain. In the following sections, the simulation results are shown. Each scheme was simulated 200 times and the receivers’ position was randomly generated. The same receivers’ positions were used for each simulation for all the schemes and for all the random cases. Receivers were distributed to the programs according to the zipf-law.
Parameters | Values
---|---
\(N_{Tx}\) | 4
\(N_{Rx}\) | 100
\(N_{\text{pro}}\) | 30
\(\text{SINR} (I)\) | 10 dB
\(G\) | \(5 \cdot 10^{-4}\)
\(\alpha\) | 4
\(\delta\) | 0 dB (non-fading), 8 dB (fading)
\(\theta\) | 0.95
\(N\) | \(6 \cdot 10^{-8}\)

Table 1 Values of the Parameters

6.1 Coverage Probability

In this section, the coverage probability for both random cases i.e. both homogeneous case and heterogeneous cases are presented. The first sub-section presents the coverage probability for the non-fading model and the following sub-section illustrates the coverage probability for the fading model, comparison of the non-fading and the fading model in terms of coverage probability is shown.

6.1.1 Non-Fading

The coverage probability remains same for the respective scheme in the different random cases, therefore in the following bar graph (see figure no. 40) the coverage probability is illustrated, which reflects all the random cases. The SINR value for the following comparison has been chosen as 10 dB. The figure shows the coverage probability figure for random cases. The X-axis represents schemes (from A to G) and the Y-axis represents the coverage probability (from 0 to 100) for the corresponding scheme. It is seen that scheme A, B, and C have a low coverage probability (84.81%) as they are focused on the MFN. Although scheme F uses single frequency for all the transmitters but does not utilize transmitter grouping, hence behave as non-SFN. As a result of the non-SFN nature, scheme F has also low coverage like MFN schemes. Remaining schemes are based on SFN which as predicted increases the coverage area thus reduces the outage probability. Scheme D, E and G offer 14.03% increase in the coverage probability (96.71%). As seen that the coverage probability for MFN (non-SFN) and SFN schemes remain constant for the respective scenarios, hence in the
next figure (see figure no. 41), the coverage probability for these two scenarios for SINR value between 0 dB and 20 dB are shown.

Figure 40 Coverage probability for Random Cases

Figure 41 Coverage probability (MFN (non-SFN) vs. SFN) for Random Cases
From the figure no. 41, it is seen that till SINR 2 dB, both cases have the coverage probability 100%. The coverage probability decreases after 2 dB for MFN case; however, as for SFN case it remains 100% till SINR 7 dB. Coverage probability starts to decrease after 7 dB in SFN. Hence, from this it is seen that SFN has a diversity gain of 5 dB. Moreover, the MFN has 84.81% coverage probability at 10 dB and SFN provides the same coverage at around 15 dB. This also indicates the diversity gain of approximately 5 dB. The increase in coverage probability means the data rate is same. However, if the coverage probability remains constant then the data rate increases. This diversity gain leads to an increase in the channel capacity i.e. data rate which is calculated according to the Shannon-Hartley theorem. Data rate increases by around 45% in the non-fading model. An interesting observation is the SFN gives maximum increase in coverage at 13 dB and after this SINR value the coverage probability increase tends to fall down. However, the SFN always offers better coverage probability compared to the MFN (non-SFN).

6.1.2 Fading

Fading is an important factor in wireless communications, and is almost inevitably present; hence it is important to design the wireless communications to combat for fading. However, in this thesis the focus was not on how to combat fading, rather the focus was whether fading contradicts the proposed idea. In this sub-section, the coverage probability in the presence of fading is shown. For the non-fading model case, it is observed that the coverage probability does not depend on channel selection model i.e. homogenous or heterogeneous channel selection model. Furthermore, the coverage probability changes only for the MFN and the SFN case. Figure no. 42 shows the coverage probability for all the schemes in the presence of fading which reflects both random cases. The figure indicates that, in the presence of fading coverage probability increase is not as high as was in the non-fading model. The SFN coverage probability is increased by 4.35% from the MFN at SINR 10 dB. Coverage probability decreases in both MFN and SFN case. SFN seems to suffer more than MFN in the presence of fading. Figure no. 42 illustrates this.

Figure no. 43 presents the coverage probability from 0 dB to 20 dB for the fading model. It is seen that the SFN always provides better coverage than MFN even in the presence of fading, but not as high as in the non-fading model. Moreover, the non-fading model offered diversity gain of roughly 5 dB, fading gives diversity gain of around 3 dB. And, data rate increases by 27% in fading model.

Figure no. 44 shows an insight of the comparison between non-fading and fading for both MFN and SFN cases.
Figure 42 Coverage probability for Random Cases (Fading)

Figure 43 Coverage probability (MFN(non-SFN) vs. SFN) for Random Cases (Fading)
The above figure shows how the MFN and SFN coverage probabilities vary from the non-fading to fading model. The coverage probability for MFN decreases by around 13.27% in the presence of fading at SINR 10 dB, but SFN has a drop off around 23.78% in the fading model. This indicates that SFN endures performance drop off in the fading model. However, SFN always provides better performance compared to MFN in terms of coverage probability.

**6.2 Channel Utilization**

This section describes the channel utilization in the random cases. As stated in the previous section, fading is almost always present in the wireless communication, therefore channel utilization and system spectral efficiency results are shown for the fading model only. The channel utilization calculation is further divided into two parts: channel utilization and multiuser channel utilization. Channel utilization is calculated as number of programs covered divided by the multiplication of number of channel required and the transmitter utilization; for multiuser case, instead of number of programs covered, number of covered receivers is used for channel utilization calculation. The formula can be found in the method chapter. Channel utilization shows among the seven schemes being designed which scheme is the most efficient i.e. provides better gain in the spectral efficiency.
6.2.1 Channel Utilization

The following figures show the channel utilization for each random case. The X-axis represents the schemes and the Y-axis represents the channel utilization. From the figures, it is seen that scheme B is most inefficient. Among the MFN schemes, scheme C is the most efficient. The SFN schemes provide far better performance compared to the MFN schemes. Moreover, scheme E, F and G provide better performance from scheme D. This proves that our proposed IP multicasting using single frequency schemes provide better performance than broadcasting over SFN and other MFN schemes. Furthermore, scheme F and G are better compared to scheme E. These results are more or less same in all the random cases. Scheme G is better compared to scheme F. Since scheme F has low coverage probability compared to scheme G, hence it is clear that scheme G is the most efficient scheme and is predicted to provide better spectral efficiency (see section 6.3). The figures show that scheme G provides 372%, 657%, 250%, 86%, 15% and 24% gain in channel utilization compared to scheme A, B, C, D, E and F respectively in the homogeneous case (see figure no. 45). In the heterogeneous case, scheme G provides 394%, 692%, 314%, 118%, 45% and 50% better channel utilization compared to scheme A, B, C, D, E and F respectively (see figure no. 46). Furthermore, it is evident that scheme G performs better in the heterogeneous case compared to the homogeneous case.

![Figure 45 Channel Utilization (Homogeneous Fading Case)](image-url)
Figure 46 Channel Utilization (Heterogeneous Fading Case)

Figure 47 Channel Utilization (Non-Fading vs. Fading)
Figure no. 47 shows the channel utilization comparison between the non-fading and the fading model. The X-axis represents the schemes with the odd positioned bar represent the homogeneous case and even positioned bar represent the heterogeneous case, and Y-axis represents the channel utilization. Furthermore, the blue color represents non-fading and the brown color represents fading model. It is observed that fading does not result in a big difference in terms of channel utilization performance. Scheme C and F endure a slight degradation in performance in fading, however, scheme E and G, along with scheme A provide better performance in the presence of fading. This is due to the fact that coverage probability is low.

**6.2.2 Multiuser Channel Utilization**

Figure no. 48 shows the multiuser channel utilization for each random case. It is seen that performance wise they are more or less same like channel utilization. However, the percentage point gain is better in this case. For example, scheme G was better compared to scheme B in the heterogeneous case by 692%, but in this case the gain is 810%. Scheme G remains the best scheme. In the homogenous case, scheme G gives 384%, 675%, 259%, 86%, 15% and 27% increase in percentage points as compared to scheme A, B, C, D, E and F respectively (see figure no. 48). On the other hand, in the heterogeneous case the increase percentage points are 468%, 810%, 327%, 118%, 45% and 55% respectively from scheme A, B, C, D, E and F(see figure no. 49).
Figure 48 Multiuser Channel Utilization (Homogeneous Fading Case)

Figure 49 Multiuser Channel Utilization with Fading (Heterogeneous Case)
Figure 50 shows the multiuser channel utilization comparison between the non-fading model and the fading model. It is observed that most of the schemes have degradation in performance in the fading model. Scheme A is unchanged in both cases. Scheme C, D and F suffer more compared to other schemes. SFN schemes offer better gain compared to the MFN schemes. Scheme E and G does not fluctuate that much. Moreover, scheme G in the heterogeneous case offers slightly better gain in the fading model.

6.3 System Spectral Efficiency (SSE)
In this section, system spectral efficiency (SSE) results are discussed. SSE is calculated by dividing the multiplication of channel utilization and channel capacity by the channel bandwidth. Channel capacity is calculated using the Shannon-Hartley theorem. Channel utilization is divided into two parts; similarly SSE is also divided into two parts. These are shown in the following sub-sections.

6.3.1 System Spectral Efficiency
System spectral efficiency is shown in figure no. 51 for the homogenous case. Bandwidth has been chosen as 6 MHz which is one of the available channel bandwidths for DVB-T/-H. It is observed that all the MFN schemes have a low SSE, scheme B being the worst. SFN schemes offer diversity gain roughly of 3 dB in fading
model; therefore, predictably, these schemes provide better SSE. Among SFN schemes, scheme D gives poor SSE and scheme G gives the highest gain in SSE. Scheme G gives 499%, 860%, 345%, 86%, 15% and 57% increase in SSE compared to scheme A, B, C, D, E and F respectively in homogenous case (see figure no. 51). In the heterogeneous case, scheme G also provides better performance. In this later case, scheme G offers 527%, 905%, 425%, 118%, 45% and 90% increase in SSE as compared to scheme A, B, C, D, E and F respectively (see figure no. 52). Scheme A, B and G provide better performance in the heterogeneous case compared to homogenous case. Figure no. 53 shows the SSE performance comparison between the fading and the non-fading model.
Figure 52 Spectral Efficiency (Heterogeneous Fading Case)

Figure 53 Spectral Efficiency (Non-fading vs. Fading)
From the above figure, it can be concluded that most schemes in fading model do provide low performances compared to the non-fading model e.g. scheme C, D, E and F. This is understood from the fact that the fading model had a diversity gain of 3 dB while non-fading model had a diversity gain of 5 dB. Scheme A seems to provide better performance in the presence of fading as compared to the non-fading in terms of percentage point increase. Scheme G also offers an increase in percentage point for heterogeneous case in fading model. Overall, there are no extreme fluctuations. SFN schemes remain better compared to MFN schemes for both models. Among SFN schemes, scheme D provides a low performance and scheme G remains the best scheme.

6.3.2 Multiuser System Spectral Efficiency (MSSE)

This sub-section shows the SSE for multiuser case. The results in more or less same compared to the previous case. However, the percentage point gain is better from previous case due to the percentage point increase in multiuser channel utilization from channel utilization. For example, in the heterogeneous case scheme G offers 1054% increase from scheme B for MSSE, but SSE offers 905% increase. In the homogeneous case, scheme G offers 513%, 883%, 355%, 86%, 15% and 61% increase in SSE compared to scheme A, B, C, D, E and F respectively (see figure no. 54). In heterogeneous case, scheme G gives 620%, 1054%, 442%, 118%, 45% and 97% increase in SSE gain compared to scheme A, B, C, D, E and F respectively (see figure no. 55). This shows that heterogeneous case provides a better performance.
Figure 54 Multiuser Spectral Efficiency (Homogeneous Fading Case)

Figure 55 Multiuser Spectral Efficiency (Heterogeneous Fading Case)
From figure no. 56, it can be concluded that like in SSE, MSSE also provides low performance in the presence of fading. The decrease in percentage point for the SFN schemes in terms of MSSE is a bit higher compared to SSE. The reason behind this is that the SFN had a higher drop off rate in coverage probability in the fading model. However, this does not contradict the proposed idea. As seen from the figure no. 56, that the SFN schemes provide a better performance compared to the MFN schemes with or without fading. Moreover, scheme G is the best scheme among SFN schemes.

6.4 Resource Plan Vs. SSE of Scheme G

As seen, that number of resource plan increases with the increase of number of transmitters. Therefore, it might be difficult to adapt schemes E, F and G into existing systems, for example, DVB-T/H and eMBMS for larger system with many transmitters. Hence, the idea is to use the best and most efficient resource plans. Figure no. 57 shows the resource plan vs. SSE graph of scheme G. It is observed that when scheme G utilizes 27 resource plans then it offers only 2% decrease compared to utilizing resource plan 51. Moreover, it offers only 10% decrease in SSE if 11 resource plans is used. No big fluctuation is observed. Although this would result in slight reduction in the gain in SSE and MSSE but provides better gain compared to any other scheme. For example, scheme G with 51 resource plans offers 45% increase in the SSE gain compared to scheme E in the heterogeneous fading model, but scheme G with 11 resource plans offers 32% increase in the SSE gain from scheme E (recalling that scheme E has 15 resource plans). It can be concluded that scheme G always provides better result compared to any other schemes.
Figure 57 Resource Plan vs. SSE of scheme G

Figure 58 Scheme E (15 RP) vs. Scheme G (11 RP)
6.5 Comparison Summary

Now a comparison of scheme E from scheme B and D is shown by means of a table. Table no. 2 shows the comparison of how much gain scheme E offers compared to scheme B and D. The reason behind choosing scheme B and D is that: scheme B is the DVB-T/H over MFN and scheme D is DVB-T/H over SFN. Scheme E is one of the proposed schemes for adapting in DVB-T/H, scheme G being the other. Scheme E (DVB-T/H over CT-DSFN) does not utilize transmitter shut off, in this scheme all the transmitters are always transmitting. Hence, this scheme is feasible for adaption without any change in the existing infrastructure. The table no. 2 shows that in every case, scheme E provides better performance. Scheme E can offer as high as 805% gain from scheme B and 62% as compared to scheme D.

<table>
<thead>
<tr>
<th></th>
<th>SSE</th>
<th>MSSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scheme B vs Scheme E</td>
<td>Scheme D vs Scheme E</td>
</tr>
<tr>
<td>Homogeneous (non-fading)</td>
<td>740%</td>
<td>37%</td>
</tr>
<tr>
<td>Heterogeneous (non-fading)</td>
<td>629%</td>
<td>29%</td>
</tr>
<tr>
<td>Homogeneous (fading)</td>
<td>736%</td>
<td>62%</td>
</tr>
<tr>
<td>Heterogeneous (fading)</td>
<td>592%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Table 2 Scheme E vs. Scheme B and D

The following table (Table no. 3) shows the comparison of scheme G from scheme C and scheme F. This comparison reflects the fact that scheme C resembles simple eMBMS over MFN, and scheme F is eMBMS without DSFN. Scheme G (eMBMS over NCT-DSFN) is the proposed scheme to be used with eMBMS. It can be observed that scheme G always performs better compared to scheme C and F. Scheme G can offer gain as high as 442% and 97% gain from scheme C and F respectively. Moreover, scheme G performs better in the fading model for all the cases.
<table>
<thead>
<tr>
<th></th>
<th><strong>SSE</strong></th>
<th></th>
<th><strong>MSSE</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scheme C vs Scheme G</td>
<td>Scheme F vs Scheme G</td>
<td>Scheme C vs Scheme G</td>
<td>Scheme F vs Scheme G</td>
</tr>
<tr>
<td>Homogeneous (non-fading)</td>
<td>316%</td>
<td>56%</td>
<td>339%</td>
<td>68%</td>
</tr>
<tr>
<td>Heterogeneous (non-fading)</td>
<td>279%</td>
<td>50%</td>
<td>320%</td>
<td>66%</td>
</tr>
<tr>
<td>Homogeneous (fading)</td>
<td>345%</td>
<td>57%</td>
<td>355%</td>
<td>61%</td>
</tr>
<tr>
<td>Heterogeneous (fading)</td>
<td>425%</td>
<td>90%</td>
<td>442%</td>
<td>97%</td>
</tr>
</tbody>
</table>

Table 3 Scheme G vs. Scheme C and F
7 Conclusions

In the existing DVB-T/H system, broadcasting is employed, which means TV program(s) is transmitted even if there are no viewers' for that particular program(s). This is inefficient in terms of spectrum management as the spectrum would have been wasted. Hence, IP multicasting is useful in order to manage spectrum efficiently. IP multicasting has already been in use in fixed broadband access networks; however it has never been used in the wireless TV programs distribution. In this thesis work, IP multicasting has been proposed to be used in wireless TV networks. TV programs will only be transmitted if viewers are currently interested in watching those programs with the introduction of IP multicasting for wireless TV programs distribution. The aimed applications are DVB-T/H and eMBMS.

A total of seven schemes have been designed and analyzed. They are:

- Scheme A: *Unicasting over MFN*
- Scheme B: *Broadcasting over MFN*
- Scheme C: *IP multicasting over MFN*
- Scheme D: *Broadcasting over SFN*
- Scheme E: *IP multicasting over continuous transmission dynamic SFN*
- Scheme F: *IP multicasting over non-SFN DCA*
- Scheme G: *IP multicasting over non-continuous transmission dynamic SFN*

Three schemes are based on multi frequency and remaining schemes utilize single frequency. All these schemes are evaluated for two random cases, namely, homogenous and heterogeneous networks. The homogenous network implies that all the transmitters belong to a single network and programs popularity has been made equally probable. In the heterogeneous network, the network is divided into two networks and each network operates using two transmitters. Moreover, in each network the programs’ popularity was randomized. The idea behind the heterogeneous network is that a particular program might be most popular in one network during a specific time of the day, but might not be popular in the other network. It might also turn out that both networks have the same program as the most popular program some time of the day. In the result chapter, it has been shown that SFN increases the coverage probability both with and without fading. The SFN increases the coverage probability by 14.03% and 4.35% in non-fading and fading respectively. This suggests that fading causes the coverage probability to decrease more sharply in SFN as compared to the MFN. However, as seen from figure number 41 and 43 that both the fading and the non-fading model, the SFN offers better coverage probability as compared to the MFN and this has been verified for SINR 0 dB to 20 dB.
In scheme A, each receiver requires a dedicated channel which is inefficient. Whilst in scheme B, each transmitter requires transmitting all the available TV programs—again wasteful in terms of spectrum management. Furthermore, scheme C can be compared to a simple eMBMS, and utilizes the fact that each transmitter would transmit the TV programs if viewers exist for those programs—efficient among the MFN schemes. Among SFN schemes, scheme D can be compared to today’s existing DVB-T/H and it requires only to transmit the total number of programs available since all the transmitters form a single zone. In scheme E, CT-DSFN is short for continuous transmission dynamic single frequency network. This implies that the SFN grouping is used and changed in different resource plans, and all the transmitters are transmitting at their full transmitter power. Whilst in scheme F, the non-SFN implies that the transmitter grouping is not employed and behaves like the MFN. Hence it does not increase the coverage probability from the MFN, but this scheme makes use of transmitter shut off in alternative resource plans which offers better channel utilization and thereby better system spectral efficiency (SSE). Besides in scheme G, NCT-DSFN stands for non-continuous transmission DSFN, which implies that some transmitters can be shut off during some resource plans and the SFN grouping is also employed. The transmitters are utilized efficiently which gives better channel utilization. In this way further SSE and multiuser SSE (MSSE) are achieved.

Although it is observed that SFN schemes provide a better coverage probability as compared to the MFN schemes, but in order to find out the diversity gain the coverage probability were kept equal. The fading model offers a diversity gain of 3 dB while the non-fading offers 5 dB of diversity gain. Because of this diversity gain, better channel capacity i.e. data rate is obtained. Data rate increases by 27% in the fading model. Channel capacity is calculated according to the Shannon-Hartley theorem. From the result chapter it is clear that schemes that use the SFN provide much better SSE and MSSE from the MFN schemes. The following factors contribute mainly to the better SSE and MSSE: diversity gain, channel capacity, number of covered programs, and number of covered receivers, low channel requirement, and the efficient use of the transmitters by shutting off in some resource plans. Since MSSE is a new definition used in this thesis and it depends on the number of receivers being covered, and SSE depends on the number of programs being covered, hence the percentage gains for SSE and MSSE in all the schemes are different—better in MSSE compared to SSE. As scheme F does not increase the coverage probability, it does not provide any diversity gain. Rest of the single frequency schemes offer same diversity gain, however scheme G provides better results compared to scheme E. The reason behind this is that scheme G gives better channel utilization by using fewer amounts of transmitters in some resource plans. However, number of resource plans increases as the number of transmitter increases. Therefore, the feasibility of using
this scheme for larger system requires to be examined. One of the proposals is to use most popular resource plans and discard the other resource plans for scheduling. By utilizing this approach, SSE and MSSE gain decrease in percentage points but offers better gain compared to other schemes as perceived from figure no. 58.

As stated previously that the applications aimed at are the DVB-T/H and the eMBMS. Since both applications have been standardized to use single frequency network, hence the proposed schemes are feasible to be used. However, some considerations need to be made, for example, centralization and scheduling. Since cells are synchronized in the SFN for both applications, therefore centralization does not seem to be a burden. As for scheduling, a scheduling MUX requires to be introduced in the DVB-T/H MUX center. Once the scheduling MUX is introduced, scheme E can easily be adapted into the DVB-T/H system. Feasibility of scheme G for the DVB-T/H requires more study and inspection into the DVB-T/H system in order to figure out whether the transmitter shut off can be utilized or not. As for the eMBMS, the highly simplified eMBMS is considered and feasibility of introducing the scheduling MUX to the eMBMS infrastructure requires further study.

Scheme B and scheme D resemble DVB-T/H over MFN and SFN respectively. Now, scheme E and scheme G are proposed for the DVB-T/H. Scheme E and G offers better gain compared to both scheme B and D. For example, as seen from table no. 2, that scheme E offers around 756% and 62% gain in MSSE from scheme B and D respectively in the fading homogeneous model, and for the same model scheme E gives 592% and 50% increase in SSE from scheme B and D respectively. Scheme G gives 1054% and 118% gain in MSSE from scheme B and D respectively in the fading heterogeneous model as seen from figure no. 55. Figure no. 52 indicates that scheme G gives 905% and 118% increase in SSE gain. By comparing the above results it is clear that scheme G is better compared to any other schemes.

Scheme C and scheme F resemble a simple eMBMS and eMBMS without DSFN respectively. Scheme G is proposed for the eMBMS. Scheme G can give roughly 442% and 97% gain in MSSE respectively from scheme C and F, and around 425% and 90% gain SSE respectively from scheme C and F in the fading heterogeneous model as observed in table no. 3. In the fading homogeneous model, the gain is also in higher side. Moreover, scheme G performs better in fading model compared to non-fading model. This proves that scheme G results in better SSE and MSSE compared to existing schemes.

Therefore, this increase in gain for SSE and MSSE would allow more TV programs to transmit, or an improved coverage can be achieved, or fewer spectrums can be utilized, or the number of transmitter required can be reduced.
Future Work
In this section, some of the future works that can further improve the thesis work are suggested:

- **Number of transmitters**: As stated before that number of resource plans increases with the increase of the transmitters’ number. Hence, the SFN schemes that are being designed can further be investigated with fewer or more transmitters. This would be helpful to further investigate the chances for feasibility for the DSFN schemes adaption.

- **Real world values**: The noise level, antenna gain and propagation path loss parameter values can be changed and checked with the real world i.e. practical values. This would probably provide a better idea about the practical increase in the gain for SSE and MSSE.

- **Power control**: In this thesis, it was assumed that transmitter power is always constant. In future, the power control can be explored meaning like transmitter shut off, different power values in different resource plans can be examined. By employing this method, coverage probability might increase and better gain in terms of SSE and MSSE might be achieved.

- **Larger system**: The larger system implies that increase number of transmitters along with increased number of programs and receivers.

- **MIMO antenna**: This can also be examined and expected to provide better gain.

- **Scheme G feasibility**: This requires to be examined whether scheme G can be adapted into the DVB-T/H system. Further studies and research can answer this.

- **Different PARPS algorithm**: One of the 10 PARPS algorithms has been used in this thesis. Other algorithms can be used to check the performances of the schemes. If the best PARPS algorithm is used then it is predicted that the SSE and the MSSE gain would be increased further.

- **Scheme H**: Another scheme namely “Unicasting over SFN” can be explored. This scheme can be compared to the proposed 4G LTE standard CoMP and unicasting mode of eMBMS. This will be very useful to explore as CoMP is not implemented yet. Hence, further study into this should yield in a good research.

- **Scheme I**: “Multicasting over SFN” – This scheme would allow to compare the reason of not examining multicasting in the wireless TV distribution. This will show the importance of DSFN for adapting multicasting.

Finally, further research can be carried on the comparison between the proposed DSFN schemes and eMBMS.
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Appendix

The MATLAB code for scheme E is presented. However, scheduling of scheme F and G is different from scheme E. Hence, scheduling for scheme G would follow scheme F. At the end, zipf-law distribution for both the homogeneous and the heterogeneous case are shown.

Scheme E MATLAB code (Simple Model)

% This script demonstrates the Scheme-E which is IP Multicasting over the CT-DSFN (Simple Model).

clear all % clears all
figure
colors='rgbcmkrgbcmkrgbcmkrgbcmkrgbcmk'; % each color for each TV program
color='rgbcmykwrgbcmykw';
hold all
areaside=22; %Length and height of the simulated square
resolution=areaside/5; % Resolution of the analyzed grid of receiver positions
alfa=4; % Wave propagation model exponent
G=5*1e-4; % Gain between transmitter and receiver. Depends on transmission power, antenna height, antenna direction, frequency, fading.
n0=6*1e-8; % Noise level including interference from external transmitters, outside our system. Depends on channel bandwidth in hertz.
gamma0 = 10; % Required signal to noise and interference ratio.
% Assignment plan T(r,z,i) = 1 if transmitter i is assigned to zone z of plan r
Trzi = cat(3, [1 0 0 0;0 1 0 0;0 0 1 0;0 0 0 1], [1 0 0 0;1 0 0 0;0 1 0 0;0 0 1 0],
       [1 0 0 0;0 1 0 0;0 0 1 0;1 0 0 0], [1 0 0 0;0 1 0 0;0 1 0 0;0 0 1 0],
       [1 0 0 0;0 1 0 0;0 0 1 0;0 1 0 0],
       [1 0 0 0;0 1 0 0;0 0 1 0;0 0 1 0],
       [1 0 0 0;0 1 0 0;0 0 1 0;0 0 1 0],
       [1 0 0 0;0 1 0 0;0 0 1 0;0 0 1 0],
       [1 0 0 0;0 1 0 0;0 0 1 0;0 0 1 0],
       [1 0 0 0;0 1 0 0;0 0 1 0;0 0 1 0],
       [1 0 0 0;0 1 0 0;0 0 1 0;0 0 1 0]);

% Assign and plot transmitter positions and range:
theta = linspace(0, 2*pi, 360); % divide circle by N points (length of data)
z_tx = [-5.5+1j*5.5, 5.5+1j*5.5, 5.5-1j*5.5, -5.5-1j*5.5]; % position of the transmitters
sz_z_tx=length(z_tx); %number of transmitters
% Generate square grid of receiver positions for TV programs
x_rx_vect = -areaside/4.5:4.5:areaside/3.5;
y_rx_vect = -areaside/12.5:12.5:areaside/4.5;
[x_rx, y_rx] = meshgrid(x_rx_vect, y_rx_vect);
z_rx = x_rx(:) + 1j * y_rx(:);
% z_rx = [x_rx(1) - 11 - 4.8891];
% Generate square grid of receiver positions for SFN
areaside_sfn=22; %Length and height of the simulated square
resolution_sfn=areaside_sfn/99; % Resolution of the analyzed grid of receiver positions
x_rx_vect_sfn = [areaside_sfn/2:resolution_sfn:areaside_sfn/2];
y_rx_vect_sfn = -areaside_sfn/2:resolution_sfn:areaside_sfn/2;
[x_rx_sfn, y_rx_sfn] = meshgrid(x_rx_vect_sfn, y_rx_vect_sfn);

z_rx_sfn = x_rx_sfn + 1j * y_rx_sfn;
N_Rx = length(z_rx_sfn); % total number of the receivers
N_pro = length(colors); % total number of TV programs

a = floor(N_Rx/N_pro);
sigma = 0; % standard deviation 0 dB for no fading, else 6 dB for fading
% Calculate fading effect between transmitter and receiver
% Antenna heights, antenna gain and carrier frequency determine this fading factor
F1 = 10.^(randn(N_Rx)*(sigma/10));
Npx = length(z_rx);
F = 10.^(randn(NRx, 1)*(sigma/10));
%
for j = 1:length(Trzi) % Plot zones for each resource plan
    subplot(nsubplotcols, nsubplotrows, j);
    if (j == nsubplotcols/2)
        t = title('Scheme E: IP Multicasting over CT-DSFN');
        set(t, 'FontSize', 15);
    end
    hold on
    % Plot receivers
    for k = 1:length(z_rx) % loop for the length of receivers
        for l = 0:a % Assign TV programs evenly
            if (k == ((l*N_pro)+1))
                s = 0; % make s zero after every 6 receivers
                end
                s = s + 1;
            end
            plot(real(z_rx(k)), imag(z_rx(k)), 'sk', 'LineWidth', 1,...
                 'MarkerEdgeColor', colors(rand_pro(s)), ...
                 'MarkerFaceColor', colors(rand_pro(s)), ...
                 'MarkerSize', 2);
            S(k) = rand_pro(s);
        end
        Z_pro = [S(:)]; % saving TV programs into vector
    end
    p_rx_sfn(:, :, j) = zeros(size(z_rx_sfn)); % initialize receiver power for zone
    for tx_cnt = find(Trzi(:, 1, j)), '% calculates the Rx power in zone1
        p_rx_sfn(:, :, j) = p_rx_sfn(:, :, j) + (F1.*G)./(abs(z_rx_sfn-
        z_tx(tx_cnt))).^alfa;
    end
    i1_rx_sfn(:, :, j) = zeros(size(z_rx_sfn)); % Co-channel interference from transmitters not belonging to zone
    for i1_tx_cnt = find(Trzi(:, 2, j)), '% calculating the interference Tx power
        i1_rx_sfn(:, :, j) = i1_rx_sfn(:, :, j) + (F1.*G)./(abs(z_rx_sfn-
        z_tx(i1_tx_cnt))).^alfa;
    end
    i2_rx_sfn(:, :, j) = zeros(size(z_rx_sfn)); % Co-channel interference from transmitters not belonging to zone
    for i2_tx_cnt = find(Trzi(:, 3, j)), '%
i1_rx_sfn(:,:,j) = i1_rx_sfn(:,:,j) + (F1.*G)./(abs(z_rx_sfn-z_tx(i1_tx_cnt))).^alfa; %calculating the interence Tx power
end
i2_rx_sfn(:,:,j)=zeros(size(z_rx_sfn)); % Co-channel interference from transmitters not belonging to zone
for i2_tx_cnt = find(Trzi(:,4,j).',
i2_rx_sfn(:,:,j) = i2_rx_sfn(:,:,j) + (F1.*G)./(abs(z_rx_sfn-
z_tx(i2_tx_cnt))).^alfa; %calculating the interence Tx power
end
if (tx_cnt~=0)

end
gamma_sfn(:,:,j)=p_rx_sfn(:,:,j)./(n0+i_rx_sfn(:,:,j)+i1_rx_sfn(:,:,j)+i2_r
x_sfn(:,:,j)); % calculates signal-to-noise-and-interference ratio for the zone
contour(x_rx_vect_sfn, y_rx_vect_sfn, 10*log10(gamma_sfn(:,:,j)),
[gamma0 gamma0],color(tx_cnt+1));
end
hold on
if (i_tx_cnt~=0)
gamma1_sfn(:,:,j)=i_rx_sfn(:,:,j)./(n0+p_rx_sfn(:,:,j)+i1_rx_sfn(:,:,j)+i2_r
x_sfn(:,:,j)); % calculates signal-to-noise-and-interference ratio for the zone
contour(x_rx_vect_sfn, y_rx_vect_sfn, 10*log10(gamma1_sfn(:,:,j)),
[gamma0 gamma0],color(i_tx_cnt+1));
end
hold on
if (i1_tx_cnt~=0)
gamma2_sfn(:,:,j)=i1_rx_sfn(:,:,j)./(n0+p_rx_sfn(:,:,j)+i1_rx_sfn(:,:,j)+i2_r
x_sfn(:,:,j)); % calculates signal-to-noise-and-interference ratio for the zone
contour(x_rx_vect_sfn, y_rx_vect_sfn, 10*log10(gamma2_sfn(:,:,j)),
[gamma0 gamma0],color(i1_tx_cnt+1));
end
hold on
if (i2_tx_cnt~=0)
gamma3_sfn(:,:,j)=i2_rx_sfn(:,:,j)./(n0+p_rx_sfn(:,:,j)+i1_rx_sfn(:,:,j)+i_
rx_sfn(:,:,j)); % calculates signal-to-noise-and-interference ratio for the zone
contour(x_rx_vect_sfn, y_rx_vect_sfn, 10*log10(gamma3_sfn(:,:,j)),
[gamma0 gamma0],color(i2_tx_cnt+1));
end
hold on
p_rx(:,:,j)= zeros(size(z_rx));%initialize receiver power for zone
for tx_cnt = find(Trzi(:,1,j)).',
  %calculates the Rx power in zone
  p_rx(:,:,j)= p_rx(:,:,j) + (F.*G)./(abs(z_rx-z_tx(tx_cnt))).^alfa;
end
i_rx(:,:,j)=zeros(size(z_rx)); % Co-channel interference from transmitters not belonging to zone
for i1_tx_cnt = find(Trzi(:,3,j).',
i1_rx(:,:,j) = i1_rx(:,:,j) + (F.*G)./(abs(z_rx-
z_tx(i1_tx_cnt))).^alfa; %calculating the interence Tx power
end
i1_rx(:,:,j) =zeros(size(z_rx)); % Co-channel interference from transmitters not belonging to zone
for i2_tx_cnt = find(Trzi(:,2,j)).',
i2_rx(:,:,j) = i2_rx(:,:,j) + (F.*G)./(abs(z_rx-
z_tx(i2_tx_cnt))).^alfa; %calculating the interence Tx power
end
i2_rx(:,:,j)=zeros(size(z_rx)); % Co-channel interference from
transmitters not belonging to zone
for i2_tx_cnt = find(Trzi(:,4,j)),',
i2_rx(:,:,j) = i2_rx(:,:,j) + (F.*G)./(abs(z_rx-
zTx(i2_tx_cnt))).^alfa; % calculating the interference Tx power
end
if(tx_cnt~=0) % calculates number of receivers in zone1 if zone1 is available
% calculate signal-to-interference-noise ratio in zone1
gamma(:,:,j)=p_rx(:,:,j)./(n0+i_rx(:,:,j)+i1_rx(:,:,j)+i2_rx(:,:,j));
c (:,:,j)= (gamma(:,:,j)>gamma0); % saves number of receivers in
zone1 for each resource plan
end
if(i_tx_cnt~=0) % calculates number of receivers in zone2 if zone2 is available
% calculate signal-to-interference-noise ratio in zone2
gamma1(:,:,j)=p_rx(:,:,j)./(n0+i_rx(:,:,j)+i1_rx(:,:,j)+i2_rx(:,:,j));
c1 (:,:,j)= (gamma1(:,:,j)>gamma0); % saves number of receivers in
zone2 for each resource plan
end
if(i1_tx_cnt~=0) % calculates number of receivers in zone3 if zone3 is available
% calculate signal-to-interference-noise ratio in zone3
gamma2(:,:,j)=p_rx(:,:,j)./(n0+i_rx(:,:,j)+i1_rx(:,:,j)+i2_rx(:,:,j));
c2 (:,:,j)= (gamma2(:,:,j)>gamma0); % saves number of receivers in
zone3 for each resource plan
end
if(i2_tx_cnt~=0) % calculates number of receivers in zone4 if zone4 is available
% calculate signal-to-interference-noise ratio in zone4
gamma3(:,:,j)=p_rx(:,:,j)./(n0+i_rx(:,:,j)+i1_rx(:,:,j)+i2_rx(:,:,j));
c3 (:,:,j)= (gamma3(:,:,j)>gamma0); % saves number of receivers in
zone4 for each resource plan
end
axis equal
end
legend ('TV Program 1', 'TV Program 2', 'TV Program 3', 'TV Program 4',...
' TV Program 5', 'TV Program 6');
q1=size(c);q2=size(c1);q3=size(c2);q4=size(c3); % determine size for each
saved receivers
% append zeros if size is less than total number of resource plans
c=cat(3,c, zeros(q1(1),q1(2),length(Trzi)-q1(3)));
c1=cat(3,c1, zeros(q2(1),q2(2),length(Trzi)-q2(3)));
c2=cat(3,c2, zeros(q3(1),q3(2),length(Trzi)-q3(3)));
c3=cat(3,c3, zeros(q4(1),q4(2),length(Trzi)-1));
C=[c c1 c2 c3]; % becomes the compatibility array
for j=1:length(Trzi) % calculate coverage area probability for each
resource plan
C_Rx(:,:,j) = sum(sum(C(:,:,j))); % total number of available receivers
in each resource plan
Cp(:,:,j) = (C_Rx(:,:,j)/NRx)*100; % calculate coverage probability
text(0,-12,...
['Coverage,Cp= ', num2str(Cp(:,:,j)), '%'],...
'HorizontalAlignment','center','FontSize',8);
for i=1:sz_z_tx
    ch_counter = 0; %initialize channel no. counter for each zone
    for ch_find = find(C(:,i,j)).', % finds the receivers inside the coverage
        ch_counter = ch_counter + 1; %channel no. for each receiver
        Nrx_zone(ch_counter,i,j) = Z_pro(ch_find); %receivers in each zone
    end
    plot(z_tx,'x'); %plot the transmitters position
    hold on
end
end % calculate number of channel required in each zone of each resource plan
for k=1:length(Trzi)
    subplot(nsubplotcols,nsubplotrows,k);
    for p=1:N_pro
        for i=1:sz_z_tx
            Npro_zone(:,i,p,k) = (Nrx_zone(:,i,k) == p); %TV programs in each zone
            Queue(i,p,k) = sum(Npro_zone(:,i,p,k)); %queue for each resource plan
            %single channel assigned, if more than one TV programs in each zone
            if(Queue(i,p,k)>1)
                Queue(i,p,k) = 1;
            end
            QUE(i,p,k) = Queue(i,p,k);
        end
        QUEUE(i,p,k) = Queue(i,p,k);
        NCh_zone(i,k) = sum(Queue(i,:,k)); %total number of programs in each zone
    end
    NCh_plan(k) = max(NCh_zone(:,k)); %number of channels in each resource plan
    for hh=1:length(Trzi)
        N_Pro2Rx_rp(hh) = length(find(Nrx_zone(:,:,hh)==p)); %finds the maximum program to receivers
    end
    N_Pro2Rx(p) = max(N_Pro2Rx_rp); %max program to receivers saved into the array
end
text(-6,12,...
    ['RP=' num2str(k)],...
    'HorizontalAlignment','center','FontSize',8);
text(7,12,...
    ['NCh= ' num2str(NCh_plan(k))],...
    'HorizontalAlignment','center','FontSize',8);
axis([-14 14 -14 14])
end
QU = Queue;
for k=1:length(Trzi)
    for p=1:N_pro
        if(sum(Queue(:,p,k)>1)) %if a program in different zones discard the program
            Queue(:,p,k) = 0;
        end
        if(length(find(Nrx_zone(:,k,p)==p))<N_Pro2Rx(p)) %if a program to rx is less than the maximum, discard the program
            Queue(:,p,k) = 0;
        end
    end
end
t = 0;
while sum(Queue(:))>0, % Loop for each timeslot, until there are no programs in Queue left.
    t=t+1;
    Nqueues_by_plan=squeeze(sum(any(Queue,2)));
    % finds the resource plans with most zones to programs
    [temp,r]=max(Nqueues_by_plan);
    % r is the most efficient resource plan.
    A_R2T(t)=r; % assign the resource plan
    for z=1:sz_z_tx
        p2z=find(Queue(z,:,r)); % finds programs in each zone of plan r
        if(p2z~=0) % if program is not empty
            p2z=p2z(1); % Choose one of the programs in queue - the one with lowest program number.
            A_p2zt(z,t)=p2z; % program is assigned to the zone of timeslot t
        end
    end
    Queue(:,p2z,:)=0; % Remove that program from all queues
end
figure
n_row=ceil(sqrt(N_pro+1));
n_col=ceil((N_pro+1)/n_row);
for t_plot =1:length(A_R2T)
    subplot(n_row,n_col,t_plot);
    %Programs transmitted in each timeslot
    pro2rx=A_p2zt(:,t_plot);
    %find the programs in each zone of each timeslot
    for N_pro2rx=1:length(pro2rx)
        p2zt=find(Z_pro==pro2rx(N_pro2rx));
        if((p2zt~=0)) %if program is not empty then plot the rx assigned to the programs
            plot(real(z_rx(p2zt)), imag(z_rx(p2zt)), 'sk','LineWidth',1,...
            'MarkerEdgeColor',colors(s),...
            'MarkerFaceColor',colors(s),...
            'MarkerSize',2);
            text(real(z_rx(p2zt))-1,imag(z_rx(p2zt))-1,num2str(p2zt),
            'FontSize',10);
            text(real(z_rx(p2zt))-3,imag(z_rx(p2zt))-1,'Rx', 'FontSize',10);
            text(-6,13-N_pro2rx,...
            ['Pro=',num2str(pro2rx(N_pro2rx))],...
            'HorizontalAlignment','center','FontSize',8);
        end
    end
    suj=size(gamma1_sfn(:,,:,:));
suj1=size(gamma2_sfn(:,,:,:));
suj2=size(gamma3_sfn(:,,:,:));
    contour(x_rx_vect_sfn, y_rx_vect_sfn,
    10*log10(gamma_sfn(:,:,A_R2T(t_plot))), [gamma0 gamma0],color(t_plot);
    if(A_R2T(t_plot)<suj(3))
        contour(x_rx_vect_sfn, y_rx_vect_sfn,
        10*log10(gamma1_sfn(:,:,A_R2T(t_plot))), [gamma0 gamma0],color(t_plot+1);
        end
    if(A_R2T(t_plot)<suj1(3))
        contour(x_rx_vect_sfn, y_rx_vect_sfn,
        10*log10(gamma2_sfn(:,:,A_R2T(t_plot))), [gamma0 gamma0],color(t_plot+2);
        end
    if(A_R2T(t_plot)==1)
contour(x_rx_vect_sfn, y_rx_vect_sfn,
10*log10(gamma3_sfn(:, :, A_R2T(t_plot))), [gamma0 gamma0], color(t_plot+3));
end
text(0,-12,...
'HorizontalAlignment','center','FontSize',8);
axis([-14 14 -14 14])
end
subplot(n_row,n_col,t_plot+1);
text(0,4,...
'Resource Plan Employed = [',num2str(A_R2T),''],...'
'HorizontalAlignment','center','FontSize',10);
text(0,2,...
'Number of Channels Required, NCh = ',num2str(length(A_R2T))),'...'
'HorizontalAlignment','center','FontSize',10);
text(0,-4,...
'Multiuser Channel Utilization = ',num2str(100./(4.*length(A_R2T)))'),...'
'HorizontalAlignment','center','FontSize',10);
text(0,-6,...
'Coverage Probability,Cp = ',num2str((sum(N_Pro2Rx)/NRx*100)),
'%%')...'
'HorizontalAlignment','center','FontSize',10);
axis([-14 14 -14 14])

Scheduling for scheme G (MATLAB code)

t = 0;
while sum(Queue(:, :)) > 0, % Loop for each timeslot, until there are no programs in Queue left.
    t = t + 1;
    Nqueues_by_plan=squeeze(sum(any(Queue,2)))'; % finds the resource plans with most zones to programs
    [temp,r]=max(Nqueues_by_plan); % find resource plans with the maximum number of zones with programs
    [temp_max,Nmax_queues_by_plan]=find(Nqueues_by_plan==temp); % find the resource plans with most zones
    [temp_n_tx,plan]=min(N_Tx(Nmax_queues_by_plan(:))); % find the resource plan which requires least number of transmitters
    rp=Nmax_queues_by_plan(plan); % rp is the most efficient resource plan.
    A_R2T(t)=rp; % assign the resource plan
    for z=1:size_z_tx
        p2z=find(Queue(z,:,rp)); % finds programs in each zone of plan rp
        if(p2z==0) % if program is not empty
            p2z=p2z(1); % Choose one of the programs in queue - the one with lowest program number.
            A_p2zt(z,t)=p2z; % program is assigned to the zone of timeslot t
        end
    end
    Queue(:,p2z,:)=0; % Remove that program from all queues
end
Zipf-Law (Program to receivers distribution)

% Zipf-law program to receivers distribution for homogeneous case
N_pro = 30; % total number of TV programs
n=(1:N_pro);
theta = 1/2; % rank (program p is p'th popular)
f_program= ((1./(n(:).\theta)))./sum(r)); %zipf law program frequency
% number of program to receivers distribution, NRx=number of receivers
zipf_pro2rx = round(f_program.*NRx);

% Zipf-law program to receivers distribution for heterogeneous case
N_pro=30; % total number of TV programs
NRx_net1=50; % total receivers in network1
NRx_net2=50; % total receivers in network2
NRx=sum(NRx_net1+NRx_net2); %total number of receivers receiving the
programs
pro_net1= randperm(N_pro); % programs in network 1
pro_net2= randperm(N_pro); % programs in network 2
r_pro_net1=1./(pro_net1.^theta); %rank (program p is p'th popular)
f_program_net1= ((1./(pro_net1.\theta)))./sum(r_pro_net1)); %zipf law program frequency
zipf_pro2rx_net1 = round(f_program_net1.*NRx_net1); %zipf law number of
program to receivers distribution
r_pro_net2=1./(pro_net2.^theta); %rank (program p is p'th popular)
f_program_net2= ((1./(pro_net2.\theta)))./sum(r_pro_net2)); %zipf law program frequency
zipf_pro2rx_net2 = round(f_program_net2.*NRx_net2); %zipf law number of
program to receivers distribution
% programs to receivers distribution
zipf_pro2rx = [zipf_pro2rx_net1(:);zipf_pro2rx_net2(:)];