



HAL
open science

Cooperative Retransmission of Broadcast Data Flows Via Cellular Networks

Muhammad Moiz Anis

► **To cite this version:**

Muhammad Moiz Anis. Cooperative Retransmission of Broadcast Data Flows Via Cellular Networks. Networking and Internet Architecture [cs.NI]. Télécom Bretagne, Université de Rennes 1, 2014. English. NNT: . tel-00978769

HAL Id: tel-00978769

<https://theses.hal.science/tel-00978769>

Submitted on 14 Apr 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Sous le sceau de l'Université européenne de Bretagne

Télécom Bretagne

En habilitation conjointe avec l'Université de Rennes 1

Ecole Doctorale – MATISSE

Cooperative retransmission of broadcast data flows via cellular networks

Thèse de Doctorat

Mention : Informatique

Présentée par **Muhammad Moiz Anis**

Département : Réseaux, Sécurité et Multimédia (RSM)

Laboratoire : IRISA

Directeur de thèse : Xavier Lagrange

Soutenue le 07 Fév. 2014

Jury :

M. Jean-François Héland, Professeur, INSA-Rennes (Président)

M. Salah Eddine Elayoubi, HDR, Orange Labs (Rapporteur)

M. Toufik Ahmed, Professeur, CNRS LaBRI, Université Bordeaux 1 (Rapporteur)

M. Philippe Godlewski, Professeur, Telecom ParisTech (Examinateur)

M. Pablo Angueira, Associate Professor, Université Basque Country, Espagne (Examinateur)

M. Xavier Lagrange, Professeur, Telecom Bretagne (Encadrant et Directeur de thèse)

M. Ramesh Pyndiah, Professeur, Telecom Bretagne (Encadrant de thèse)

Acknowledgements

I am whole-heartedly grateful to both of my thesis supervisors, Professor Xavier LAGRANGE and Professor Ramesh Pyndiah, for putting their faith in my potentials and choosing me to do research under their supervision. At every stage I realized that the combination of their expertise was ideal to guide me on this topic.

I am specifically indebted to Xavier for devoting his unprecedented dedication in carving a useful research work out of my efforts. It was simply an honor to have directly worked with Xavier, who has such a vast experience with cellular network technologies. I am also thankful to him for always being a reliable support and a firm advocate of myself on any administrative issue related to my stay in France. On the other hand, Ramesh also deserves my sincere thanks for bolstering the validity of this research work through his techno-economical vision and technological sagacity.

I would like to express my sincere gratitudes to the Jury members. Their insightful questions and encouraging remarks on my work made my thesis defence a learning experience as well along with being a lifelong memory. It is my utmost honor to have all these experts having evaluated this work.

I am thankful to other teaching staff of RSM department as well, especially Professor Loutfi Nuaymi and Professor Jean-Marie Bonnin for their affection and encouragement. Apart from the professors, I cannot complete such an acknowledgement without offering my special thanks to Alexander Pelov, Patrick Maille and Kamal Singh for occasional discussions on general topics. I am also thankful to my fellow PhD students and other colleagues including Guillaume et al., who made my stay very delightful and memorable in RSM by arranging recreational events annually. Also my special thanks to the non-teaching staff at the Rennes campus especially the secretary of RSM department Anais for her cooperation and Mr. Gildas Valy for his time-to-time tips on learning French language.

During my stay in Rennes I made some very good friends like Luis, Vladimir and Vasiliy, my heartfelt thanks to them for providing emotional cushion in hard times. In the end, I would like to thank my parents, my siblings and my lovely wife, Amna for their love and support. Especially, I thank my parents who sacrificed a lot to enable me traveling abroad and taking education in some of the prestigious institutes of Europe. I dedicate this work to my parents.

Abstract

Among the multimedia content distribution services to the handheld receivers, mobile TV is a popular service. Digital Video Broadcast (DVB) networks have high capacity and coverage to perform a mass multimedia content distribution. The conventional DVB networks are designed to cover fixed receivers, which have a roof antenna. The handheld receivers have different configurations which cause weaker link budgets. Generally, a broadcast system is unidirectional and it does not have a feedback channel to ensure the reception of the data at the receiver side.

On the other hand, cellular networks have more reliable bidirectional links with the handheld receivers. Individual multimedia transmission to each handheld receiver generates a huge load in the cellular networks. In the specific example of mobile TV, it is not efficient to regenerate the same transmission load for each handheld receiver. In our thesis work, we consider a cooperation between the broadcast systems and the cellular networks for an efficient multimedia reception at the handheld receivers. We use the cellular network link for the retransmission of the lost packets from a multimedia broadcast data-flow reception.

In this work we analyze the coverage for handheld receivers in a single frequency broadcast network. We specifically consider several outdoor and indoor scenarios in a DVB-T2 network. We analyze how a data flow is processed in DVB-T2 and propose a scheme for the identification of packets in the DVB transmission. The core contribution of our thesis work is the proposition of a Real-time Flow Repair (RFR) Service based on cellular network, which repairs any multimedia data-flow to the handheld receivers in real-time. The proposed RFR service is based on a light client-server application protocol, namely Constrained Application Protocol (CoAP). The RFR proposal is also supported by the analysis of the load generated in LTE Radio access network due to RFR service.

Keywords

mobile TV; multimedia; handheld; DVB-T2; LTE; broadcast; unicast; repair; coverage; real-time; Cellular network; data-flow; PLP; SFN; smartphones

le Résumé de la thèse en Français

Contexte

Parmi les services de distribution de contenu multimédia vers des récepteurs portatifs, la télévision mobile est un service populaire. Les réseaux de diffusion vidéo numérique (DVB) offrent à la fois une grande capacité et une bonne couverture pour effectuer une distribution massive de contenus multimédias. Les réseaux DVB conventionnels sont conçus pour couvrir des récepteurs fixes avec une antenne sur le toit. Les récepteurs portatifs ont des configurations différentes qui présentent un moins bon bilan de liaison

En règle générale, un système de diffusion est unidirectionnel et il n'a pas une voie de retour pour assurer la réception des données sur le côté du récepteur. D'autre part, les réseaux cellulaires ont des liens bidirectionnels plus fiables avec les récepteurs portatifs. Lorsqu'on effectue une transmission d'un contenu populaire en propre vers chaque récepteur portable, cela génère une énorme charge dans les réseaux cellulaires. Dans l'exemple spécifique de la télévision mobile, il n'est pas efficace de régénérer la même charge de transmission pour chaque récepteur portable. Dans notre travail de thèse, nous considérons une coopération entre les systèmes de diffusion et les réseaux cellulaires pour une réception multimédia efficace et de qualité au niveau des récepteurs portatifs. Nous utilisons la liaison réseau cellulaire pour la retransmission des paquets perdus dans un flux de données de diffusion multimédia.

Contribution des Travaux

Les contributions de notre travail de thèse sont représentées comme suit :

- Nous évaluons les pertes de couverture pour les récepteurs portatifs dans un réseau DVB. Nous considérons les cas typiques et évaluons les pertes de bilan de liaison pour différents scénarios intérieurs et extérieurs. L'évaluation est fondée sur les calculs mathématiques pour la non disponibilité de service DVB dans un modèle de densité de population typique urbain i.e. modèle de densité de Clark et un modèle de densité trafic véhiculaire i.e. modèle de densité de Smeed.

- Nous analysons le même problème de couverture pour les récepteurs portatifs dans un réseau DVB à fréquence unique (SFN). L'analyse est basée sur les travaux de simulation, où les caractéristiques des réseaux SFN DVB sont étudiées à la lumière du rapport signal sur interférence et bruit (SINR) dans la zone de la cellule et de sa relation avec la distance de l'utilisateur et du phénomène d'auto-interférence.
- Nous proposons une méthode pour l'identification unique d'un paquet DVB-T2 (i.e. BB-frame) dans le système DVB-T2. Cette identification est basée sur les informations de signalisation dans chaque trame OFDM d'une transmission DVB-T2.
- Nous proposons un service de réparation d'un flux en temps réel (Real-time Flow Repair, RFR) basé sur le réseau cellulaire, qui peut réparer n'importe quel flux de données multimédia de diffusion pour les récepteurs portatifs. La notion de temps réel est justifiée sur la base de caractériser une transmission DVB comme un flux de données continu vers les récepteurs portatifs. Les opérations de réparation sont basées sur un protocole client-serveur qui s'appelle Constrained Application Protocol (CoAP). Nous étudions le service proposé pour les smartphones recevant une transmission DVB-T2 dans un réseau LTE
- Nous proposons également une infrastructure commune prévue pour les réseaux LTE et DVB. L'infrastructure proposée est basée sur la mise en œuvre du serveur RFR, qui est considéré comme un nœud commun entre les deux infrastructures i.e. le DVB-T2 et le LTE Evolved Packet Core (EPC). Les serveurs de RFR sont considérés à plusieurs emplacements dans l'infrastructure, en utilisant des techniques de déchargement dans les réseaux cellulaires i.e. Selected IP Traffic Offload (SIPTO) et Local IP Access (LIPA).
- Nous évaluons le surplus de charge sur le réseau d'accès radio (RAN) du réseau cellulaire en raison de la retransmission des éléments manquants de la transmission DVB pour les récepteurs portatifs. Nous considérons la charge des paquets DVB en nombre de blocs des ressources cellulaires. La contribution majeure a été la recherche d'un compromis entre la charge de réseau cellulaire et la puissance de transmission DVB. Ce compromis est étudié pour plusieurs tailles de cellules du réseau cellulaire. Nous considérons une transmission haute définition (HD) DVB-T2 pour les récepteurs portatifs dans le réseau Long Term Evolution (LTE).

Conclusion

Dans notre travail de thèse, nous préservons l'intégrité des piles de protocoles des deux domaines i.e. réseaux DVB et LTE . Le service de RFR proposé est conforme aux procédures dans le réseau LTE. Dans le cas de l'insertion de contenu régional la transmission du contenu multimédia DVB provient d'une venue locale ou régionale dans le réseau DVB, nous proposons l'utilisation des techniques de déchargement pour réparer une transmission DVB régionale i.e. SIPTO et LIPA. Dans ces deux techniques

de déchargement la pile de protocole LTE est intact et la fonctionnalité de PGW est placée dans une passerelle locale i.e. LGW dans chacun des deux cas .

Dans le chapitre 6 , nous montrons que le réseau LTE a une capacité suffisante pour la charge supplémentaire causée par la retransmission des paquets de transmission DVB. De même, dans la section 5.5, nous présentons les valeurs de délai maximum de RTT dans la littérature, qui sont assez courts par rapport à la durée typique des trames DVB. Nous en concluons donc que la réparation d'un flux en temps réel basé sur LTE sur la transmission DVB -T2 peut être atteint. Dans notre proposition, nous insistons sur le fait d'avoir un protocole d'application léger, pour cette raison nous fondons le service RFR sur CoAP.

Mots-clés

la télévision mobile ; multimédia ; récepteurs de poche ; DVB-T2 ; LTE ; diffusion ; unicast ; réparation ; couverture ; en temps réel, le réseau cellulaire ; flux de données ; PLP ; SFN ; smartphones

Contents

List of Abbreviations	xvii
List of symbols	xxi
List of Figures	xxv
List of Tables	xxvii
Glossary	xxxii
1 Introduction	1
1.1 Context of the thesis work	1
1.2 Contribution of the Thesis work	2
1.3 Organization of the Thesis Report	4
2 Digital Video Broadcast Networks	7
2.1 Historical context for today's DVB network	8
2.1.1 Evolution to Digital Transmission	8
2.1.2 Digital Video Broadcasting standardization	8
2.1.3 Aims and objectives of the DVB-T2 standard	9
2.1.4 Input Formats	10
2.2 System Overview	10
2.2.1 Concept of Physical Layer Pipes	13
2.3 Single Frequency Broadcast Networks	14
2.3.1 Conceptual understanding of a Single Frequency Network	14
2.3.2 Single Frequency Network Model	16
2.4 Extended OFDM parameter-set for DVB-T2	18
2.5 Preliminaries for the Simulation work	19
2.5.1 Fundamental Configuration	19

2.5.2	Propagation Model	22
2.6	SINR distribution in DVB SFN	25
2.6.1	SINR distribution in the cell area	28
2.6.2	SINR profile along the cell radius	30
2.7	Summary	31
3	Handheld Coverage in DVB networks	33
3.1	DVB standardization for the handheld reception	34
3.1.1	Global Handheld TV Broadcast business	34
3.1.2	Technological Limitations of the handheld standards	34
3.1.3	State-of-the-art on the Handheld TV Broadcast	35
3.2	Handheld Receiver scenarios	36
3.2.1	Link Budget	37
3.2.2	Propagation Model	38
3.3	Outage in the Cell Area	40
3.3.1	Smeed's Urban Population density	43
3.3.2	Clark's Urban population density	44
3.4	Coverage Analysis of the two population density models	47
3.5	Handheld receivers in a DVB SFN	50
3.5.1	SFN Scenario and the parametric values	50
3.5.2	Signal Propagation	50
3.6	Simulation Results	51
3.7	Summary	54
4	DVB-T2 Frame Structures	55
4.1	Logical Frame Structure	55
4.1.1	GS/TS Streams	56
4.1.2	Baseband Frames (BB-frame)	57
4.1.3	FEC Frame	58
4.1.4	FEC-Blocks	59
4.1.5	Interleaving Frame	60
4.1.6	Time Interleaving (TI)-block	61
4.2	Physical Frame Structure	62
4.2.1	T2-Frame	63
4.2.2	OFDM cells	64
4.2.3	Mapping of PLPs into the T2-Frames	64

4.2.4	P1-Symbol	67
4.2.5	Superframe	67
4.2.6	Future Extension Frames	67
4.2.7	Dummy cells and Auxiliary Streams	68
4.3	Layer 1 (L1)-Signaling	68
4.3.1	P1-Signaling	68
4.3.2	L1-presignaling	69
4.3.3	L1-postsignaling	70
4.4	Summary	73
5	Real-time Flow Repair Service based on LTE network	75
5.1	Introduction	76
5.2	Service Proposal	77
5.2.1	Context	77
5.2.2	Real-time Flow Repair (RFR) Service definition	77
5.3	Realtime Repair with Constrained Application Protocol (CoAP)	78
5.3.1	Introduction to Constrained Application Protocol (CoAP)	80
5.3.2	CoAP based RFR Service	81
5.4	Identification of the DVB unit data packet	81
5.4.1	BB-frame identification for the RFR service	81
5.4.2	Specification of the RFR service procedures	84
5.5	LTE Round Trip Time (RTT) Latency effects on the RFR service	88
5.6	RFR Server Location	90
5.6.1	Evolved Packet System	90
5.6.2	EPS bearer	91
5.6.3	RFR servers enabling a joint infrastructure	91
5.7	Summary	96
6	DVB retransmission load over LTE network	97
6.1	Preliminaries	98
6.1.1	Fundamental Configuration	98
6.1.2	Propagation Model	100
6.2	LTE Resource Allocation	101
6.3	DVB Transmission Power and Loading of the LTE network	102
6.3.1	Load Evaluation	103
6.3.2	Number of the Pairs of Resource Blocks	105

6.4	Parametric values and Simulations	106
6.4.1	Parametric Values	107
6.4.2	Simulation Results	108
6.5	Summary	112
7	Conclusion	113
7.1	Summarizing the elements	113
7.2	Conclusive Remarks	114
7.3	Prospective Research directions	115
7.3.1	RFR service via eMBMS bearers	115
7.3.2	RFR service Scheduling	115
7.3.3	RFR Bearer modification for RFR operation over regional DVB data flow	116
7.3.4	Home-RFR server for indoor DVB handheld receivers	116
A	Outage probability derivation	117
A.1	Smeed's population density	117
A.2	Clark's population density	119
B	Error performance modelling	121
	List of Publications	123
	Bibliography	124

List of Abbreviations

ACK	Acknowledgement message
ANR	l'Agence Nationale de la Recherche
BB-Frame	Base Band - Frame
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDF	Cumulative Distribution Function
CNR	Carrier to Noise Ratio
COFDM	Coded OFDM
CON	Confirmable Message
CoAP	Constrained Application Protocol
CRC	Cyclic Redundancy Check
DVB	Digital Video Broadcast
DVB-H	DVB - Handheld
DVB-T2	DVB - 2 nd Generation Terrestrial
DVB-NGH	DVB - Next Generation Handheld
DVB-C	DVB-Cable
DVB-S	DVB-Satellite
DVB-SH	DVB- Satellite Handheld

EBU	European Broadcast Union
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
eUTRAN	evolved Universal Transmission RAN
FEC	Forward Error Correction
FEF	Future Extension Frame
FER	Frame Error Rate
FFT	Fast Fourier Transform
FLUTE	File Delivery over Unidirectional Transport
GI	Guard Interval
GS	Generic Stream
GSE	GS Encapsulation
GCS	Generic Continuous Stream
GFPS	Generic Fixed-length Packet Stream
HARQ	Hybrid Automatic Repeat reQuest
HDTV	High Definition Television
ISD	Intersite Distance
ISDB-T	Integrated Service Digital Broadcast - Terrestrial
ISN	Implicit Sequence Number
IPDC	IP DataCasting
LTE	Long Term Evolution
LIPA	Local IP Access
LDPC	Low Density Parity-check Code
LOS	Line Of Sight
MBMS	Multimedia Broadcast Multicast Service
M3	Mobile MultiMedia
MID	Message ID
MIMO	Multiple Input Multiple Output
MPEG	Motion Picture Expert Group

MPTS	Multi Program Transport Stream
MISO	Multiple Input Single Output
NON	Non-confirmable Message
OFDM	Orthogonal Frequency Division Multiplex
PLP	Physical Layer Pipe
PAPR	Peak to Average Power Ratio
PDN	Packet Data Network
PGW	PDN Gateway
PRB	Pair of Resource Blocks
QEF	Quasi Error Free
QAM	Quadrature Amplitude Modulation
QPSK	Quad- Phase Shift Keying
RFR	Realtime Flow Repair
RAN	Radio Access Network
RST	Reset Message
RTT	Round Trip Time
SAE	System Architecture Evolution
SFN	Single Frequency Network
SIPTO	Selective IP Traffic Offload
SISO	Single Input Single Output
SINR	Signal Interference Noise Ratio
SGW	Serving Gateway
SMS	Short Message Service
TI-block	Time Interleaving-block
TFS	Time Frequency Slicing
TS	Transport Stream
TSPS	Transport Stream Partial Stream
TSPSC	TSPS Common
TTI	Transmission Time Interval
T-DMB	Terrestrial-Digital Multimedia Broadcasting
T2-MI	T2-Modulator Interface
TCP	Transport Control Protocol
UDP	User Datagram Protocol
URL	Uniform Resource Locator
WLAN	Wireless Local Area Network
3GPP	3 rd Partnership Project

List of symbols

B	Signal bandwidth
b	Exponential decay parameter from Clark's model
b_{fr} and k_{BCH}	Number of bits per BB-frame / BB-frame length / Information word length for BCH coding
B_{PRB}	Width of a pair of resource blocks in frequency axis of the LTE OFDM frame i.e. 180 kHz
c	Speed of the light
C_{plan}	Average power level planned by the operator for the edge DVB users
C_m or C_{min}	Minimum carrier signal power received by a fixed or a handheld receiver
C/N	Carrier to Noise Ratio
D	Intersite distance among the DVB transmitters in SFN
D_{LTE}	Intersite distance between eNBs
d_{LOS}	The maximum distance till which there is a LOS between the DVB transmitter and the receiver
D_q	Distance of the q^{th} ring from the centre in an SFN
F	Noise of Figure of the receiver

f_c	Signal 's carrier frequency
G_{iso}	The handheld antenna gain for the given signal
g_{frac}	Guard Interval Fraction
h_{DVB}	DVB transmitter height
h_{eNB}	The antenna height for an eNB
h_r	Receiver 's antenna height
h_t	Transmitter height
k	Boltzman constant
L_{dB}	Total average path loss
L_f	Feeding cable loss in dB
L_o	The distance-independent part of the average path loss also excluding indoor penetration loss
L_T	The distance-independent part of the average path loss also including indoor penetration loss
N_0	Noise power in dB
n_{BCH}	The codeword length of the BCH coding or information word length for the LDPC coding
n_{LDPC}	The codeword length of the LDPC coding or FEC-frame length
$P_{s,i}$	The received signal power from i^{th} DVB transmitter in the SFN
$P_{t,i}$	The transmission power from the i^{th} DVB transmitter or eNB
q	Ring index for transmitters, which are equidistant from the centre of the central cell in an SFN
R	The DVB cell radius
R_{LTE}	LTE cell radius
R_e	Radius of earth
$ \vec{r}_{eNB} $ or r	Radial distance of DVB receiver from the centre in the central of the SFN
r_{user}	Source data rate received a DVB user from a given PLP

S_i	Spectral efficiency of the LTE radio link for i^{th} DVB handheld receiver in the LTE network
T	Thermal noise temperature
T_{etu}	Elementary time unit specific to the T2-system bandwidth selection
T_g	Guard interval time duration
T_p	Maximum delay for which self-interference is partial
T_s	OFDM symbols duration
T_u	Time duration of the user data signal in the OFDM symbol
$w(\tau)$	Fractional weight for the signal and interference powers in an SFN
ΔC	Additional signal strength required by the handheld receiver w.r.t. the fixed one
ΔL_T	Configurational deficit for a handheld receiver w.r.t. the fixed one
ϵ_s	Average DVB service outage experienced by a user
$\epsilon(r)$	DVB service outage as a function of the receiver's distance from the transmitter
ξ	A lognormally distributed random variable
γ	Average path-loss coefficient
χ	Correlation coefficient for the standard deviation of the correlated shadow fading
$\rho(r)$	Population density as a function of the distance
σ	The standard deviation of the overall signal variation
σ_{cn}	Standard deviation of the common part for the correlated shadow fading
σ_i	Standard deviation of the shadow fading for the signal indoors
σ_o	Standard deviation of the shadow fading for the signal outdoors
σ_{ucn}	Standard deviation of the uncommon part for the correlated shadow fading
τ_i	Delay of the i^{th} signal version w.r.t. the earliest one in an SFN transmission
θ	Azimuth angular position of the receiver in the DVB cell

List of Figures

2.1	Block diagram of a DVB T2 end to end chain	11
2.2	A generic model for the DVB T2 modulator[1]	12
2.3	Concept of Physical Layer Pipes in a T2-system	15
2.4	Guard Interval in a DVB-T2 OFDM symbol	15
2.5	Contributions from the SFN member transmitters	16
2.6	1- $w(\tau)$ i.e. Self-interference Profile	17
2.7	The considered deployment of DVB cells	20
2.8	Distance of the q^{th} ring, D_q	21
2.9	Central DVB cell: DVB receivers placement	21
2.10	DVB Transmitters over Earth 's surface	24
2.11	Maximum distance with Line of Sight, d_{LOS}	24
2.12	CDF of user SINR values for ISD = 50 km	27
2.13	SINR vs Distance, for ISD = 50 km and outdoor conditions	27
2.14	SINR vs Distance, for ISD = 31 km and outdoor conditions	28
2.15	SINR vs Distance, for ISD = 24 km and outdoor conditions	28
2.16	SINR vs Distance, for ISD = 50 km and indoor conditions	29
3.1	Three cases considered for the DVB-T2 reception[2]	37
3.2	Comparison of the outage at a given distance	42
3.3	Smeed Population distribution for $i = -1.8$	44
3.4	Smeed Population distribution for $i = 0$	44
3.5	Smeed Population distribution for $i = 4$	44
3.6	Clark's Population distribution for $\frac{\rho_o}{\rho_e} = 1.01$	45

3.7	Clark's Population distribution for $\frac{\rho_o}{\rho_e} = 10$	45
3.8	Outage probability curves	47
3.9	DVB-T2 coverage and Urban Population density	49
3.10	A DVB-T2 SFN designed to cover fixed receivers	51
3.11	Fixed vs Handheld receiver coverage in a SFN	53
4.1	DVB-T2 Transmission chain	56
4.2	BB-frame structure for Normal Mode[1]	58
4.3	BB Frame Formation for Normal Mode	60
4.4	Interleaving frame	61
4.5	The three standardized cases of Time interleaving	62
4.6	DVB T2 Physical Framing structure[3]	63
4.7	Pilot and active OFDM cells in Normal and Frame closing symbols[3]	64
4.8	Mapping order of the Data PLP Subslices along the increasing cell index in a T2 frame [3]	65
4.9	T2-frame mapping with different types of PLPs	66
4.10	L1 Signaling structure	69
4.11	L1-presignaling fields categorized as per their utility	69
4.12	Important fields from the L1-postsignaling Configurable part	71
4.13	L1-postsignalling Dynamic part	72
5.1	A simplified Architectural layout	79
5.2	A simplified timing diagram of an RFR operation	79
5.3	RFR service via LTE network for a simple implementation of CoAP	82
5.4	BB-frames Sequence order prior to the followed transformation	82
5.5	The LTE transmission delay and the BB-frame identification	83
5.6	Major steps prior to repair operation	85
5.7	Repair operations along with the Broadcast data flow	85
5.8	PLP switching	86
5.9	RFR SF_COUNT rationale	89
5.10	National RFR Server	92

5.11	Regional RFR Server	92
5.12	Town-level RFR Server	94
5.13	RFR servers integrated into the LTE core network and the DVB-T2 System	95
6.1	DVB vis-a-vis LTE deployment considered	99
6.2	Central DVB cell: Handheld 's placement	99
6.3	The composition of a LTE subframe	102
6.4	LTE bandwidth Allocation	103
6.5	FER performance curves for DVB-T2 data signals	104
6.6	Lost BB-frames per sec in terms of PRBs per TTI	106
6.7	Max number of lost BB-frames per second per user for given distance of eNode B	109
6.8	PRBs per eNB per TTI vs eNB ring index, for $D_{LTE} = 8.66$ km	109
6.9	PRBs per eNB per TTI vs eNB ring index, for $D_{LTE} = 5.2$ km	110
6.10	PRBs per eNB per TTI vs eNB ring index, for $D_{LTE} = 1.73$ km	110
6.11	PRBs per eNB per TTI vs Fractional distance in DVB central cell, for DVB Tx Power = 64 dBm	111
6.12	PRBs per eNB per TTI vs Fractional distance in DVB central cell, for DVB Tx Power = 68 dBm	111

List of Tables

2.1	OFDM Parametric values	19
2.2	Values for i , j and k	19
2.3	Parametric Values for the SFN	26
3.1	Link Budget	38
3.2	Total deficit in Power loss for the handheld receivers	40
3.3	Handheld receivers in Smeed 's population density	48
3.4	Handheld receivers in Clark's population density for $\frac{\rho_o}{\rho_e} = 10$	48
3.5	Parametric Values	52
4.1	FEC Coding parametric values	59
5.1	RFR Exchanges: RFR Client to RFR Server	84
6.1	LTE Network Capacity for different Bandwidths [4]	102
6.2	Values for the parameters of the BER model	104
6.3	Parametric Values for the DVB SFN	107
6.4	Parametric Values for LTE Network [5],[6]	108

Glossary

BB-frame	A BB-frame is the fundamental data unit of the logical framing structure of a DVB-T2 system.
Bearer	A bearer is a path for the data transmission across the LTE core with a defined priority, capacity, delay and packet loss rate
Configurational deficit	The dB difference between the distance independent average path losses of a handheld and a fixed DVB receivers.
Default Bearer	A bearer forms a logical connection between the UE and the PDN. when a UE connects to PDN it is assigned a Default Bearer, which carries an IP address (if PDN is IP network).
Generic Stream (GS)	A Generic stream comprises variable length packets, which are generally IP Packets.
Guard Interval	The cyclic repetition of the useful part of a DVB-T2 OFDM symbol, to avoid inter-symbol interference.
Implicit Sequence Number	The index number for a BB-frame implicitly known to the DVB decoder/ encoder as per the natural sequence of the BB-frames prior to the FEC coding stage.

Integrated antenna	An-	An antenna designed to receive radio signals on the LTE frequencies and considered to receive lower band signals like DVB signals as well in EBU 3348 [7].
Interleaving frame		A scheduling unit frame for a given PLP which comprises several T2-frames. The T2-frames are interleaved as per the structure of the interleaving frame for the respective PLP.
Local-Gateway (LGW)		A gateway used in the LTE offloading techniques to enable a data breakout at an alternative local venue instead of PGW.
Local IP Access (LIPA)		A technique enabling UE to access a local IP network via eNB and avoiding the user plane to traverse LTE core network.
LTE Resource Element		An LTE Resource Element is the finest resource for the LTE resource allocation. It is defined as the LTE OFDM subcarrier available for the duration of one OFDM symbol.
OFDM cell		It is defined as the availability of a DVB OFDM subcarrier for one OFDM symbol. The Physical resources in a T2-frame are assigned in terms of the OFDM cells for each PLP.
Pair of Resource Blocks		It is the finest unit for the physical resource allocation to each UE in an LTE network. Along time axis it spreads over one LTE sub-frame i.e. 1 ms. Each resource block is 180 kHz wide.
Packet Data Network Gateway, (PGW)		The PGW is the entry and exit point for the user data traffic from the packet data network (e.g. IP network) into the LTE core network.
Physical Layer Pipe	Layer	The Physical Layer Pipes (PLP) are defined as multiplexed channels each with a pre-defined level of robustness and data rate.

Radio Horizon	The maximum distance allowing a line-of-sight between a radio transmitter and receiver if the curvature of the earth is considered.
RFR session	An on-going realtime repair activity over a broadcast data flow to the RFR client, which engages the RFR server and the RFR client into data exchanges. An RFR session is specific for a given PLP.
Round Trip Time	It is the total time in which an RFR client sends a repair request to the RFR server and receives an acknowledgement along with the answer to the request by the RFR server.
Selected IP Traffic Offload (SIPTO)	A technique used to have default bearer from an IP network via a closer LGW. The LGW can be co-located with a SGW or in the LTE access network.
Self-interference	The interference experienced by a signal from its other versions arriving later at the receiver end. Those signal versions are transmitted by other transmitters in the SFN.
Serving Gateway (SGW)	A SGW serves as a packet forwarding entity between the LTE access and core networks.
SF_COUNT	It is defined as the superframe count field maintained at RFR server and RFR client for the unique identification of a superframe in a given RFR session.
Single Frequency Network	A group of transmitters simultaneously transmitting same signal at same carrier frequency form a Single Frequency Network.

Smartphones	A handheld multimedia-capable device having a wireless radio link with the cellular networks.
Superframe	A bigger frame of the DVB physical framing structure comprising several T2-frames.
Time Interleaving-block	A group of FEC-blocks from a given PLP. The cells of FEC-blocks are time interleaved within a TI-block structure.
Time Frequency Slicing	A technique which allows the use of multiple RF carriers for a given DVB transmission.
Transmission Time Interval	The time interval in which an LTE subframe or a Pair of Resource Blocks is transmitted i.e. 1ms.
Transport Stream	A stream of fixed-size packets comprising MPEG flows.
T2-frame	The unit frame of the DVB physical framing structure comprising OFDM symbols.
T2-gateway	A T2-Gateway delivers a sequence of T2-Modulator Interface (T2-MI) stream at its output. This T2-MI stream contains the DVB transmission data, the signalling information and the transmission time of the DVB-transmission.
T2-modulator	T2-modulator uses the instructions contained in the incoming T2-MI stream and accordingly creates and emits the OFDM frames of the DVB-T2 transmission at the configured time.
T2-System	A set of transmissions having time-synchronized frame structure, same physical layer parameters, same number and type of PLPs and identical physical signaling.

1.1 Context of the thesis work

The arrival of highly capable multimedia handheld devices foretells about a potentially mature market for the dissemination of high definition multimedia content. Among the multimedia services the most commonly demanded is mobile TV service [8, 9, 10]. The present wireless multimedia transmission technologies are divided into two groups: wireless broadband and broadcast technologies. Among the broadband technologies cellular networks have the strongest leverage for multimedia transmission to the smartphones. A mobile TV transmission symbolizes a continuous multimedia broadcast data flow to the handheld receivers [11]. In this regard the Digital Video Broadcast (DVB) networks are an appropriate choice, because of their wide coverage areas and a broadcast oriented infrastructure.

The broadcast of a high definition content to the handheld receivers has been an interesting topic for both the cellular network and the broadcast standardization bodies. The European Telecommunication Standards Institute (ETSI) proposed some handheld Digital Video Broadcast (DVB) standards like DVB-Handheld (DVB-H) and DVB-Satellite Handheld (DVB-SH) in the mid of the previous decade. Those standards did not succeed because of the lack of a denser deployment of cell sites [12], [9], [13] and the absence of a massive handheld-oriented multimedia market [14]. The DVB 2nd generation Terrestrial standard (DVB-T2) also includes some parameter-sets for the handheld receivers coverage. Moreover, in November 2012, a pre-standardization document A160 [15] about DVB-Next Generation Handheld (DVB-NGH) has been released.

Just half a decade ago a cellular network based mobile TV service over the best effort unicast bearers was proposed. The mentioned service could also not succeed due to the lack of an appropriate business model for a mass market of the handheld receivers with the advanced multimedia capabilities [9]. Since release 6 of the 3GPP

standards the 3rd Generation Partnership Project (3GPP) has also proposed some multimedia broadcast services e.g. Multimedia Broadcast Multicast Service (MBMS) [16] and Integrated Mobile Broadcast (IMB). The recent proposal of 3GPP in this regard is evolved MBMS (eMBMS).

At the same time we know that there have been discussions between the Third Generation Partnership Project (3GPP) and DVB standardization communities to evolve an inter-technological cooperation for the high definition mass multimedia distribution and TV transmission to the handheld receivers, [13]. In [17] authors proposed the concept of an Integrated Communication and Broadcast Networks (ICBNs). The solution proposes the use of a conventional broadcast network for several proposed-services with an out-of-band interactivity via mobile communication technologies, e.g. 3G and WLAN. The French stance on this issue takes this convergence to a level of proposing a joint physical layer for the mobile phones receiving multimedia from the state-of-the-art cellular and broadcast networks i.e. eMBMS and DVB-NGH respectively in the Mobile Multimedia (M3) Project of l'Agence Nationale de la Recherche (ANR) [18, 19].

1.2 Contribution of the Thesis work

A broadcast transmission is conventionally unidirectional. Thus a DVB transmitter is indifferent to the loss of elements at the reception side. The DVB signals are coded using Forward Error Correction (FEC). The FEC coding gain in the link budget reduces the error rate at a lower signal power level compared to the previous broadcast technologies.

But the handheld receivers are situated in a different configuration as compared to a conventional fixed DVB receiver with roof antenna. For example they have a higher probability of having no line-of-sight with the DVB transmitter, nor they can have a high gain antenna like fixed receivers.

To solve the problems of handheld coverage with the existing infrastructure, one pre-dominant idea is to have some diversity from Multiple Input Multiple Output (MIMO) and other spatial techniques [20, 15]. In a DVB-T2 network it is also possible to transmit the same content over robust modulation and coding schemes for the DVB handheld receiver. Then several questions arise: to what extent this compensates the link budget deficits for handheld receivers? and how it avoids the consequent DVB service outage for the handheld receivers?

The retransmission of the missing elements for a bad signal reception is a classical way to improve the reliability of a non-ideal reception. In a conventional broadcast we do not have a bidirectional link and therefore we do not have feedback signals to trigger a partial or complete retransmission.

Contrary to the physical layer convergence between the cellular and the broadcast networks, this thesis work is based on the idea of a cooperative interworking of the two domains. The primary focus is to explore the cellular networks in the role of a retransmission mechanism for the multimedia broadcast data flows to the handheld receivers.

We consider the case of a smartphone receiving the DVB transmission for which the cellular network retransmits the lost elements from the DVB reception at each smartphone on-ground. We characterize this retransmission as a realtime repair process over the broadcast data flows to the handheld receivers. The contributions of our thesis work can be accounted as:

- We evaluate the typical coverage losses for the handheld receivers in a Digital Video Broadcasting network. We consider typical cases from the standardization reports and evaluate the link budget losses for different indoor and outdoor scenarios. The evaluations were based on the mathematical derivations of the DVB service outage in a typical urban population density i.e. Clark's density model and an urban vehicular traffic density model i.e. Smeed's density model.
- We analyze the DVB handheld coverage problem for Single Frequency Networks (SFNs) also. The analysis is based on simulation work, where the characteristics of the DVB SFNs are studied in the light of the Signal to Interference and Noise Ratio (SINR) distribution in the cell area and its relationship with user distance and 'Self-interference'.
- We propose a method for the unique identification of a DVB-T2 logical data packets (i.e. Base Band - frames) in a DVB-T2 system. This identification is based on the signaling information in each OFDM frame of a DVB-T2 transmission.
- We propose a Real-time Flow Repair (RFR) service based on the cellular network, which can repair any digital multimedia broadcast data flow to the handheld receivers. The proposition of a realtime repair is justified on the basis of characterizing a DVB transmission as a continuous data flow to the handheld receivers. The repair operations are based on a light client-server application protocol i.e. Constrained Application Protocol (CoAP). We study the proposed service for the

smartphones receiving a DVB-T2 transmission in a Long Term Evolution (LTE) network.

- We also propose a joint infrastructure for the DVB and LTE networks to support RFR service. The proposed infrastructure is based on the implementation of the RFR server, which is considered as an overlapping node between the two infrastructures i.e. DVB-T2 system and the LTE Evolved Packet Core (EPC). The mentioned RFR servers are considered at several location in the infra-structure, using famous offloading techniques in the cellular networks i.e. Selected IP Traffic Offload (SIPTO) and Local IP Access (LIPA).
- We evaluate the load on the Radio Access Network (RAN) of the Cellular network due to the retransmission of the missing elements from the DVB transmission to the handheld receivers. In this regard we consider the DVB data packets load in terms of the cellular network resource blocks. One of the major contribution is the establishment of a trade off between the Cellular Network loading and the DVB transmission power. This trade off is studied for different inter-site distances in the cellular network. We consider a DVB-T2 High Definition (HD) transmission to the handheld receivers in the LTE network.

1.3 Organization of the Thesis Report

The thesis report is organized into seven chapters, which include:

- In Chapter 2 we provide a synopsis of the characteristics of a typical DVB network. We consider a state-of-the-art DVB network i.e., which is structured on the basis of some additional parameters and new concepts. We focus on the concept of the Physical Layer Pipes (PLPs). We also study the SFN networks properties and the SINR distribution in a DVB-T2 network.
- In Chapter 3 we focus on the handheld coverage issue in a DVB network. We evaluate the link budget deficits for the handheld receivers in the indoor/outdoor scenarios and determine the corresponding coverage losses for two well-known population density models. We also evaluate the DVB service outage for the handheld receivers in a DVB SFN.
- In Chapter 4 we study the physical and logical packet structures of the DVB-T2 technology. We also include a brief review of the physical layer signaling in a

DVB-T2 frame structure. In the end of this chapter we highlight the fields which are useful for the unique identification of a DVB-T2 logical data packet.

- In Chapter 5 we propose the RFR service, which is based on the retransmission of missing DVB data packets via an RFR server in the cellular network. We elaborate on the procedural steps of the RFR service. The RFR service is based on CoAP, therefore we include a brief study on CoAP also. We also review some basic definitions pertinent to the LTE networks, to aid the readers for understanding the location of the RFR servers in the LTE core network.
- In Chapter 6 we consider a double coverage scenario for the handheld receivers. We evaluate the additional load over the cellular network due to the retransmission of the missing data packets from the DVB transmission to the handheld receivers. We also study the relationship between the DVB transmission power and load over the cellular network for different cell sizes in the cellular network.
- In Chapter 7 we present the conclusion of this thesis work. We summarize the findings from each part of the thesis work, propose our conclusive remarks and identify the prospective work directions.

Digital Video Broadcast Networks

A Digital Video Broadcast (DVB) Network is a dedicated network which performs a continuous broadcast of the media content. In this chapter we discuss the main features of a typical broadcast network. The details of those salient features are specific to DVB-2nd Generation Terrestrial (DVB-T2) Network, which is the present state-of-the-art DVB network. In Section 2.1 we highlight the history of video broadcasting and give the context in which DVB-T2 was released. In Section 2.2 the overall picture of a DVB-T2 System is presented, from the content generation to its distribution. Moreover, we explain the novel concept of Physical Layer Pipes in a DVB-T2 system. In section 2.3 we explain the concept of a Single Frequency Network (SFN) and present a well-known SFN model followed by a discussion about the parameters selection for that model. Section 2.4 comments on the choice of parameter values for a DVB-T2 system. Section 2.5 describes a SFN scenario and the propagation model for the simulations. The signal propagation model includes Okumura-hata as the path loss model, a model for the correlated shadow fading, the Signal to Noise Ratio(SNR) evaluation and the presentation of the formula calculating the radio horizon for a given set of the network parameters. In Section 2.6, we present and discuss the simulation results. The simulations were conducted to evaluate the performance of the DVB-T2 SFNs in the context of handheld indoor and outdoor scenarios. We focus on the SINR distribution in the DVB central cell and its relation with the position of a DVB receiver. Section 2.7 summarizes all the main results of this chapter and links the findings with the coming-up chapter.

2.1 Historical context for today's DVB network

2.1.1 Evolution to Digital Transmission

Historically, Paul Nipkow can be recognized as the founding father of Picture transmission. He devised a setup in 1883 called Nipkow disc, which transmitted a picture by dissecting it into lines. The first analog TV transmission took place in 1930 but the technology could not flourish much because of the World War II till the 1950s. The era of 1960s can be marked by the introduction of the coloured analog TV Transmission.

According to W. Fischer in [21], in 1980s many attempts were made to digitize TV transmission and in early 90s Digital TV was implemented in labs but it was just not possible to transmit Standard Definition TV of 270 Mbps on any of the available Carrier technologies i.e. Cable, satellite and terrestrial. The situation was even worse for High Definition Television (HDTV) transmission which demanded 1.5 Gbps extendable to 3 Gbps. The introduction of powerful video compression by Motion Picture Expert Group (MPEG) format in early nineties paved the way to Digital TV transmission. The MPEG-2 is capable of compressing a digital TV signal of 270 Mbps down to 4 to 7 Mbps and the stereo audio signal of about 1.5 Mbps to typically 192 kbps. Due to these high compression ratios it is possible to combine several programs on one 8 MHz analog TV channel. [21]

2.1.2 Digital Video Broadcasting standardization

In 1993 a unanimous framework was set and the foundation of Digital Video Broadcasting (DVB) Project was laid by Broadcasters, Equipment providers/ manufacturers and regulators in Europe¹.

Initially, DVB project considered a couple of standards in parallel. The DVB-Satellite (DVB-S) standard offered 38 Mbps on QPSK modulated satellite links, which could support 6 to 10 TV channels. This capacity could support 20 audio channels as well. Similarly, DVB-Cable (DVB-C) based on Coaxial Cable offered a 38 Mbps for a 8-MHz bandwidth by employing 64 QAM modulation scheme. The Hybrid Fibre Coax could even support a data rate of up to 50 Mbps. [21]

¹It is comprised of 230 members [22]

DVB-Terrestrial (DVB-T) offered 5-31 Mbps capacity and it was first adopted by Britain in 1998. Typically, it offered 22 Mbps to the roof antenna receivers. The offered capacity reduced to 11-15 Mbps for the portable receivers moving at low speed. However, MPEG-2 was the common choice in the baseband signal for all these standards. [21]

The DVB standards like DVB-C, DVB-S and DVB-T belong to the first generation of the DVB standards. The launch of DVB-Satellite 2nd generation (DVB-S2) in 2002 marks the second generation of the family of standards and following it DVB-Cable 2nd generation (DVB-C2) and DVB-Terrestrial 2nd generation (DVB-T2) were also introduced. The 2nd generation of the DVB standards is characterised by the introduction of Coded-Orthogonal Frequency Division Multiplex (COFDM), inclusion of the Low Density Parity-check Code (LDPC) in the Forward Error Correction (FEC) coding chain and the use of very large Fast Fourier Transform (FFT) sizes like 16k and 32k for Orthogonal Frequency Division Multiplex (OFDM) ². DVB-T2 was first launched in 2009 in UK and two years later was deployed in Italy, Sweden, Finland and Zambia [23]. In countries where DVB-T services are already on air, DVB-T2 is likely to co-exist with DVB-T. As from the experiences in Australia (DVB-T, MPEG-2 video coding) and France (DVB-T, MPEG-4 video coding) it has been established that the HDTV services are perfectly viable without using DVB-T2.

2.1.3 Aims and objectives of the DVB-T2 standard

The DVB T2 was expected to achieve some targets prior to its launch. Those targets can be considered as a fundamental framework for the DVB-T2 technology. One of the major features was to provide a 30% gain in capacity w.r.t. ³ DVB-T [3]. A DVB-T2 system is based on OFDM but uses an extended set of the parametric values compared with a DVB-T system. For example DVB-T2 uses the famous Low Density Parity Check (LDPC) codes in its FEC coding chain, which are capable to achieve a link capacity close to Shanon limits [24, 25, 3]. The highest order constellation used is a 256-Quadrature Amplitude Modulation (QAM). Moreover, for DVB-T2 transmission the OFDM symbols may have a Guard Interval Fraction (GIF) as large as $\frac{1}{4}$. A DVB-T2 system uses eight different pilot patterns and the Fast Fourier Transform (FFT)

²The FFT size is almost equal to the number of subcarriers in the OFDM frame 's bandwidth, which has an impact on the capacity and coverage of the network

³with respect to

size for its OFDM signal can be 16k and 32k. Thus it outclasses the DVB-T system in terms of both capacity and coverage.

An important aspect is the backward compatibility with the domestic antennae at the receiver side already used to receive the DVB-T signal. The DVB-T2 technology is based on the same infrastructure as for the DVB-T transmitter, [3]. Given the same infrastructure DVB-T2 technology gives a better coverage to the fixed receivers with the roof antennae. In the context of the reception at the portable (i.e. slow moving) and handheld receivers T2-lite or T2-mobile profile was also introduced in 2011[26], which included some new parametric values specific to the handheld receivers.

Another objective of the DVB-T2 technology is to transmit different versions of the same data flow, with different levels of robustness and video quality. For instance, it is expected to have a more robust version of the same service which enables handheld receivers also to get adequately covered.⁴

2.1.4 Input Formats

There are four types of Input formats which DVB-T2 can support:

- Transport Stream (TS), which is a stream based on the MPEG format fixed size packets.⁵
- Generic Stream (GS), which comprises variable length arbitrary packets, generally IP packets
- Generic Continuous Stream (GCS), which is a Generic Stream where the modulator is not aware of the packet boundary.
- Generic Fixed-length Packet Stream (GFPS), which is a generic stream comprising packets of fixed length.

2.2 System Overview

The end-to-end chain of DVB T2 system has been divided into five sub-systems [3]. There are three sub-systems on the network side and two on the receiver side as shown in Figure 2.1.

⁴This refers to the concept of the Physical Layer Pipes (PLP) in a DVB-T2 modulator and demodulator, which we present in detail in section 2.2

⁵TS are supported in the second generation of DVB to have backward compatibility

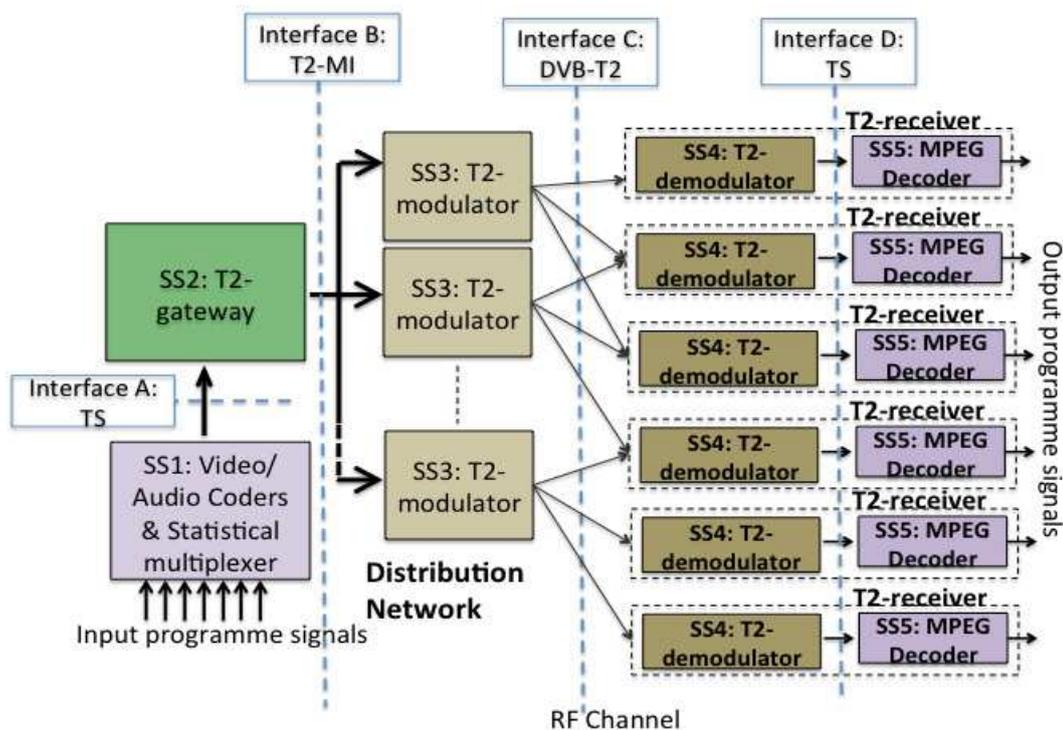


Figure 2.1: Block diagram of a DVB T2 end to end chain

Coding and Multiplexing Sub-System (SS1)

The SS1 is the first subsystem of the T2-system chain. SS1 is next to the signal generation which occurs outside the T2-system. SS1 generates a TS and/or a GS by multiplexing a number of input program signals. Particularly for video services it generates the video/audio encoding and associated program guide or the service information and other Layer 2 (L2) signalling.

T2-gateway Sub-System (SS2)

A T2-Gateway delivers a sequence of T2-Modulator Interface (T2-MI) streams at its output. This T2-MI stream contains the DVB transmission data, the signalling information and the transmission time of the DVB-transmission.

A single T2-MI stream is fed to one or more T2-modulators in the distribution network. Each T2-MI packet may contain a logical DVB packet (i.e. Base Band-frame), signaling information or the data packet of an auxiliary stream. Each T2-MI stream packet carries information about the mapping of the logical DVB packets to the Orthogonal Frequency Division Multiplexing (OFDM) based physical frames (i.e.

T2-frame) and some information about the time duration of the OFDM frame. Thus, scheduling and capacity allocation are two of the major functions of a T2-gateway.

Modulator Subsystem (SS3)

SS3 uses the instructions contained in the incoming T2-MI stream and accordingly creates and emits the OFDM frames of the DVB-T2 transmission at the configured time. In some configurations it is also possible to add the T2-gateway functionalities in the modulator subsystem. In that case the TS (i.e. coded and multiplexed input program signals) is directly fed to the modulator [3, 1]. In [1] modulation process is defined to start from the mode/ stream adaptation and to end at the OFDM frames transmission.

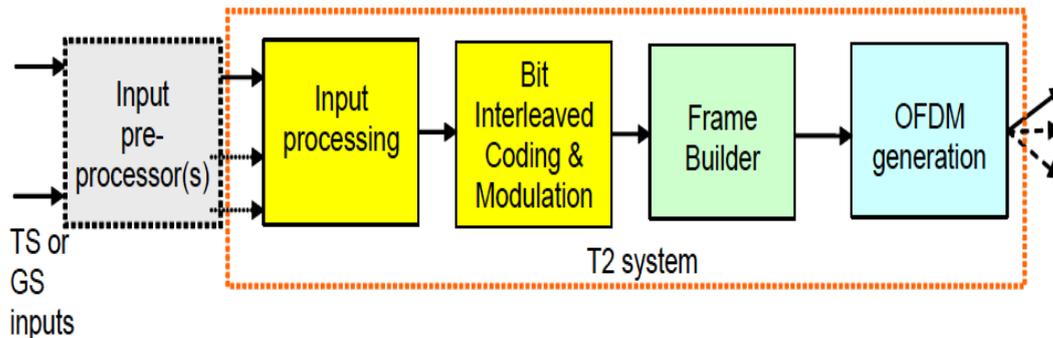


Figure 2.2: A generic model for the DVB T2 modulator[1]

A generic T2-modulator model including all the steps involved before the up-conversion and transmission of a DVB-T2 signal is illustrated in Figure 2.2. The input format for a T2-modulator is either one or multiple logical data flows. The input pre-processing step serves as a service-splitter or demultiplexer which provides a valid input to the T2-modulator. In the input processing block TI-stream blocks are read to extract the DVB data packets. In the next step those packets are coded with the Forward Error Correction (FEC) coding, then bit-interleaved and are mapped on the constellation points as per the modulation scheme scheduled. The last two stages i.e. the Frame building and OFDM generation correspond to the generation of the OFDM frames.

The typical output of a T2-modulator is a single RF signal. But there can be another output signals to be conveyed through another transmitting antenna [1]. Such mode of transmission is called Multiple Input Single Output (MISO). In [3] Alamouti-based MISO is considered, in which the second antenna of each modulator transmits

a slightly modified and the frequency reversed version. This technique yields some diversity gains for the link budget.

T2-demodulator subsystem (SS4)

SS4 receives an RF signal and gives a transport or generic stream by extracting the data packets from the DVB signal which is based on OFDM frames.

Stream decoder subsystem (SS5)

SS5 receives the transport stream and outputs the video and audio decoded. This sub-system is essentially the same for all DVB standards.

2.2.1 Concept of Physical Layer Pipes

The Physical Layer Pipes (PLP) are defined as multiplexed channels each with a pre-defined level of robustness and data rate [26]. The PLP is a newly introduced concept in the 2nd generation of DVB standards. A PLP carries one TS/GS or any logical data flow at a time. The robustness and associated throughput of a PLP depend on the nature of the service and the sensitivity of the receiver [27].

The previous DVB standards were single PLP systems such that the programs had to be multiplexed in a Multi-Program Transport Stream (MPTS). The transport of a MPTS via DVB-T2 OFDM frames enables an efficient DVB reception compared to the one through the framing structure of a DVB-T system.

The DVB-T2 system re-multiplexes or splits a MPTS into several Transport Stream Partial Streams (TSPSs) and a Transport Stream Partial Stream Common (TSPSC), which carries the common part from all the TSPSs (see Annex D of [1]). The mentioned TS splitting process takes place prior to the Input processing block of the DVB-T2 modulator (see Figure 2.2).

Because of the PLP oriented structure of a DVB-T2 frame (refer to Chapter 4) a receiver can skip decoding and de-multiplexing of the entire MPTS. A DVB-T2 receiver can only decode the PLP carrying the relevant TSPS. The TSPSs obtained from a MPTS are assigned a group of PLPs. A group may also have one common PLP which carries the TSPSC. There may not be any common PLP if there is no MSPSC.

The PLPs from a single source (i.e. bearing the TSPSs from a MPTS) typically have same modulation, coding and interleaving depth, as a common PLP contains data

shared by the data PLPs of the group. Thus in order to receive the relevant TSPS, the receiver has to receive the corresponding common PLP also along with the respective data PLP. Generally, a common PLP carries common interest data like higher layer signaling, program guides or other shared service components.

To transmit a High Definition (HD) or 3-Dimensional (3D) service, high data rate PLP is needed (For example PLP 2 in Figure 2.3). For these services a PLP having high code rate and high order constellation is preferable. To receive and correctly decode a high code rate and high order constellation signal, a high level of SINR is required. In this regard the DVB receivers with a roof-top antenna have strong link budgets to support the reception of such a signal. On the contrary, for transmitting a standard definition signal to a handheld receiver or a radio broadcast service, a PLP offering low data rate but with a better robustness is suitable.

Although the major advantages of having PLPs are receiver-specific, PLPs also enable an efficient insertion of the regional services at the network side. We can define a T2-system as a set of transmissions having time-synchronized frame structure, same physical layer parameters, same number and type of PLPs and identical physical signaling. However, a PLP in some cases may carry different content in the case of the local content insertion. There can be some PLPs bearing local content, such a content is specific to the DVB cell. In Figure 2.3 the insertion of a regional TS for a regional DVB transmitter is shown. In Figure 2.3 we highlight n PLPs carrying n different services and their versions. A receiver identifies local transmission by the field of Cell_ID in the physical layer signaling (refer to Chapter 4).

2.3 Single Frequency Broadcast Networks

2.3.1 Conceptual understanding of a Single Frequency Network

In a Single Frequency Network (SFN) the same signal is transmitted from multiple sources i.e. transmitters in the network. Each signal version transmitted by a transmitter farther than the closest one has some propagation delay w.r.t. the signal version arriving first. The impact of each of the signal versions over the cumulative strength of the signal depends on its delay w.r.t. the earliest version.

An Orthogonal Frequency Division Multiplexing (OFDM) symbol is protected by a cyclic prefix and in the case of DVB signal that prefix is called a Guard Interval (GI). GI comprises cyclic repetition of the user data signal in the OFDM symbol. The OFDM symbols duration T_s is defined by $T_s = T_u(1 + g_{frac})$, where, T_u is the time

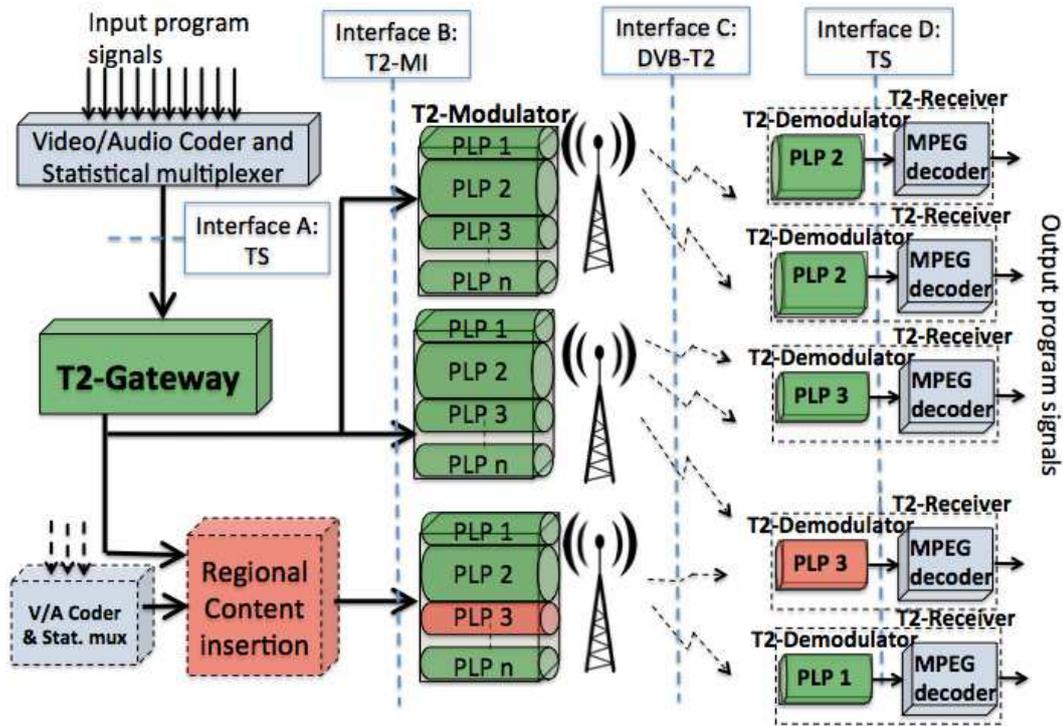


Figure 2.3: Concept of Physical Layer Pipes in a T2-system

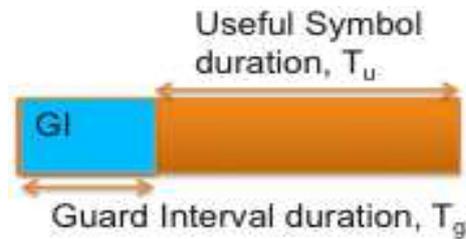


Figure 2.4: Guard Interval in a DVB-T2 OFDM symbol

symbol that carries actual user data signal and g_{frac} is the Guard Interval Fraction (GIF). (see Figure 2.4)

Generally, a signal version arriving within the GI of the first version contributes positively in all, to the total strength of the signal. The versions arriving partially within the GI contribute only to the relevant fraction to the signal strength. The fraction of the signal beyond the GI causes interference to the Signal as shown in Figure 2.5.

The SFNs have proven to be more efficient for broadcast applications compared to other diversity gain based broadcasting techniques [28]. DVB-T2 has a greater choice of FFT sizes, guard intervals and pilot patterns compared to its predecessor. Therefore,

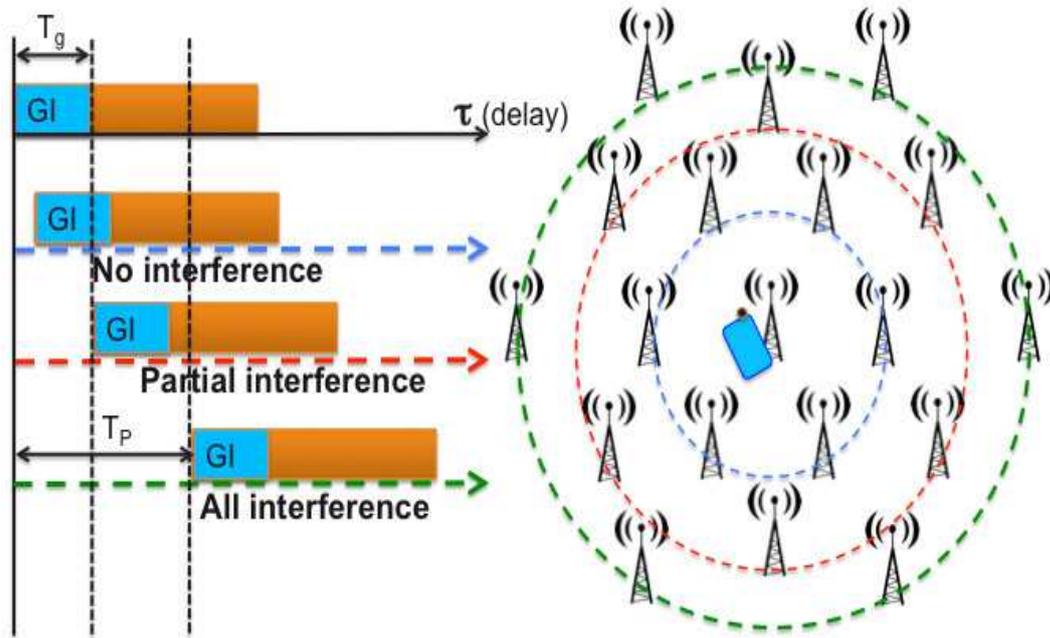


Figure 2.5: Contributions from the SFN member transmitters

it is very interesting to have a closer look at the way SINR is distributed in the DVB-T2 SFN coverage area.

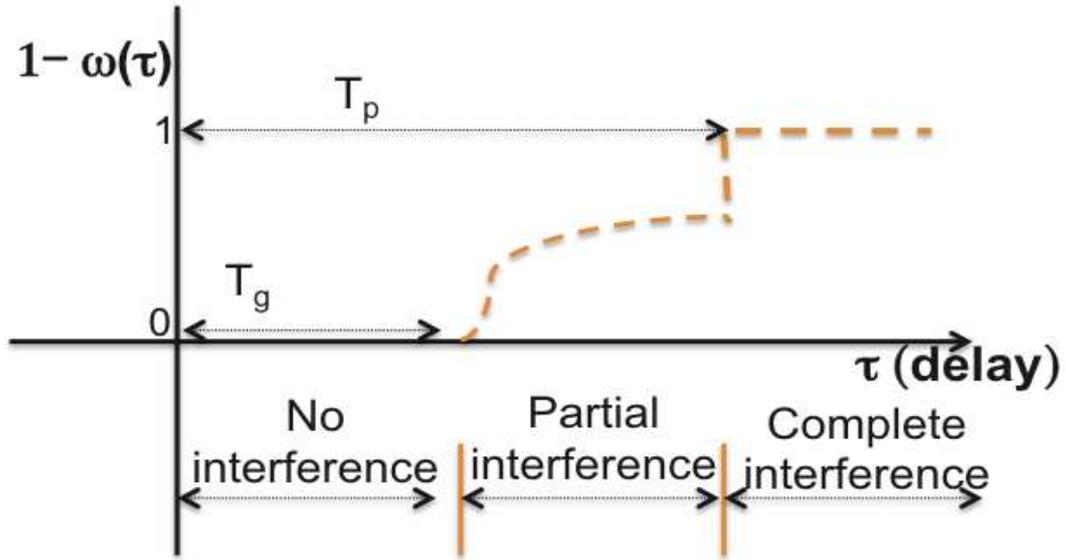
2.3.2 Single Frequency Network Model

Depending on the delay, τ , for each signal version w.r.t. the firstly arrived version, the contribution of each version is either full or partial to both the signal power or the interference power as shown in Figure 2.6. In the case of partial contribution the non-contributing part of the signal serves as a source of "Self-interference" [7]. Hence, the Signal to Interference Noise Ratio (SINR) for SFN can be given as,

$$SINR = \frac{\sum_i w(\tau_i) P_{s,i}}{N_0 + \sum_i (1 - w(\tau_i)) P_{s,i}}, \quad (2.1)$$

where, $P_{s,i}$ is the power received and τ_i is the time delay (i.e. w.r.t. the first signal arrived) from the i^{th} DVB Transmitter.

Function $w(\tau)$ gives a fractional value depending on τ . In [29] a simple model is presented, where the value of $w(\tau)$ is linearly related to τ . In [30] the $w(\tau)$ has been modeled as quadratic function of τ for the DVB-T SFN. The model presented in [30] for DVB-T is also adopted for the analysis of a DVB-T2 SFN in [7]. The $w(\tau)$ function as given in [7] is,

Figure 2.6: $1-w(\tau)$ i.e. Self-interference Profile

$$\begin{aligned}
 w(\tau) &= 1 & 0 \leq \tau < T_g, \\
 &= \left(\frac{T_u - \tau + T_g}{T_u} \right)^2 & T_g \leq \tau < T_p, \\
 &= 0 & T_p \leq \tau,
 \end{aligned} \tag{2.2}$$

where, T_u is the useful symbol length, T_g is the guard Interval time and T_p is the maximum delay for which the self-interference is partial. In [30] T_p is roughly considered to be $2T_g$ or $\frac{T_u}{3}$ for a DVB-T SFN.

In [7] T_p is defined as the equalization interval, which has a certain position on Time scale. The start of this interval is determined by the receiver, in this work we assume the interval to start with the arrival of the first SFN signal. Contrary to DVB-T, the value of T_p depends on the choice of the FFT size, guard interval and the choice of equalization methods as explained in section 4.2 of [7]. For the values of the parameters considered in Table 2.3, we take the equalization interval⁶, $T_p = \frac{T_u}{3}$.

⁶Refer to Table 4.2 of [7] and Table I.5 of [1]. Moreover, in the network planning applications the equalization Interval is simply taken as $\frac{57}{64}$ of the Nyquist limit [7].

2.4 Extended OFDM parameter-set for DVB-T2

A DVB-T2 system can have 1.7, 5 and 10 MHz bandwidths additionally along with the 6, 7 and 8 MHz bandwidths used for a DVB-T system. The DVB-T2 standard also introduced some additional sizes for the Fast Fourier Transform (FFT) in the OFDM modulation. In an OFDM modulator the FFT size is directly related to the number of OFDM sub-carriers in the bandwidth. As the number of sub-carriers for a given bandwidth increases the inter-sub-carrier spacing reduces, which results in wider OFDM symbols. Hence, for bigger FFT sizes the delay tolerance increases because of the longer symbol durations.

At high frequency bands like UHF Band IV/V the doppler shift can be wide enough to cause inter-sub carrier interference for the signals having a narrow sub-carriers spacing. For example for L-band operation i.e. 1.5GHz, a 1k FFT size gives the best Doppler performance.⁷

The number of sub-carriers in the normal carrier mode varies from 853 to 27,265 for a range of FFT sizes 1k to 32k in a 8 MHz bandwidth T2-system, Table 2.2 of [7]. The extended carrier mode can only be used for the FFT sizes 8k, 16k and 32k.

For extended mode the additional number of subcarriers for 8k, 16k and 32k FFT sizes on each side of central frequency is 48, 144 and 288 respectively. For a 8 MHz bandwidth the frequency spacing (for any FFT size) between the two edge sub-carriers of the band is 7.61 MHz in normal carrier mode and for extended mode it is 7.77 MHz⁸. But due to a variable number of sub-carriers, the carrier spacing for 1k to 32k FFT size varies from 8.93kHz to 279 Hz respectively.

As the symbol duration is directly related to the FFT size, the larger is the FFT size, the longer is the OFDM symbol. The symbol duration is $1024T_{etu}$ for 1k and $32,768T_{etu}$ for the 32k FFT size, where T_{etu} is the elementary time unit specific to the T2-system bandwidth selection, for a 8 MHz bandwidth, $T_{etu} = 7/64 \mu s$, Table 2.3 [7]. The highest order constellation used by a DVB-T2 network is 256-QAM, which is possible due to the high FEC coding gains in a DVB-T2 system [3]. A DVB-T2 network can be planned for a larger set of GIFs w.r.t. a DVB-T network. In Table 2.1 a summary of the values for some of the important OFDM parameters is presented.

⁷For a fixed bandwidth 1k FFT have the widest carrier spacing 8.93 kHz for a 8MHz bandwidth. Doppler Shift in frequency is higher for a higher carrier frequency

⁸Selection between extended and normal carrier mode does not change the sub-carrier spacing.

Table 2.1: OFDM Parametric values

Bandwidth	1.7, 5, 6, 7, 8, 10 MHz
T_{etu}	71/131, 7/40, 7/48, 1/8, 7/64, 7/80 μ s
FFT size	1k, 2k, 4k, 8k, 16k, 32k
Guard Interval Fraction	1/128, 1/32, 1/16, 19/256, 1/8, 19/128, 1/4
No. of Sub-carriers	853, 1705, 3409, 6817, 13633, 27265
Extended No. of sub-carriers	0, 0, 0, 96, 288, 576
Modulation	BPSK, QPSK, 16-QAM, 64 QAM, 256 QAM

Table 2.2: Values for i , j and k

q	m_{max}	i	j	k	D_q/D
1	6	1	0	1	1
2	6	1	1	3	1.73
3	6	2	0	4	2
4	12	2	1	7	2.64
5	6	3	0	9	3

2.5 Preliminaries for the Simulation work

2.5.1 Fundamental Configuration

We consider a layout of hexagonal DVB cells comprising q rings of equidistant cells around the central one. The DVB cell radius, R , can be related to an Inter-site Distance (ISD) of D km as, $R = \frac{D}{\sqrt{3}}$. Each cell has a transmitter, with an antenna height of h_{DVB} in meters. A q^{th} ring at a distance D_q from the central DVB site is classically given by,

$$D_q = \sqrt{k}D, \quad (2.3)$$

where, $k = i^2 + ij + j^2$, the positive integers i and j determine k in ascending order for the increasing values of q in Figure 2.7. In Figure 2.8 we demonstrate a simpler view of the SFN, where the equidistant DVB transmitters are illustrated to have rings of radii D_q for $q = 1-3$. The values of q , i , j , h are shown in Table 2.2 as well as the number of transmitters m_{max} in each ring. The value of m_{max} changes according to the classical axioms [31].

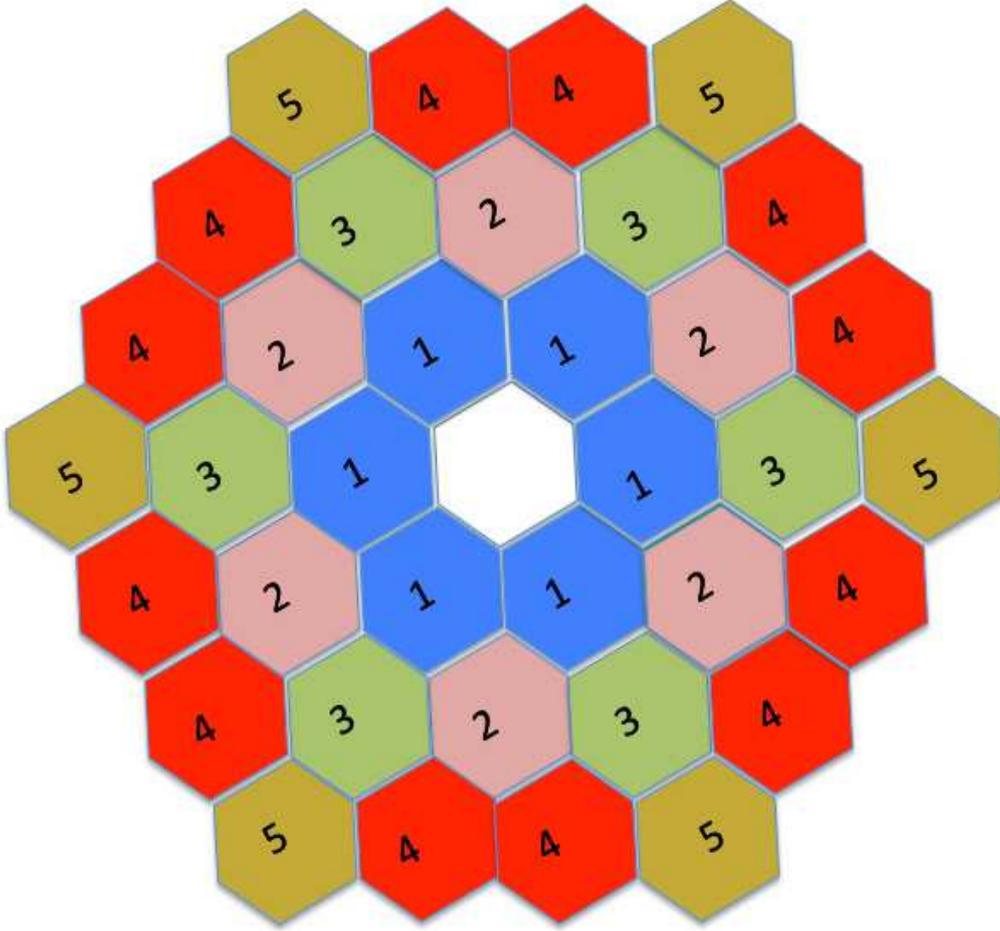


Figure 2.7: The considered deployment of DVB cells

In Figure 2.9 we consider two arrangements for the DVB receivers in the central DVB cell.

- Case 1: Uniform distribution of n DVB receivers
- Case 2: Equidistant n DVB receivers around the DVB Tx

If we consider the centre of the central DVB cell as the origin, then the position of each DVB transmitter can be determined by $\vec{D}_{q,m} = D_q \hat{m}$, where \hat{m} is the unit vector in the direction of the m^{th} transmitter in the q^{th} ring. We point a receiver's position in the central cell by \vec{r}_{eNB} .

The time delay, τ for any signal version is calculated w.r.t. the earliest signal version at the DVB receiver. In other words the delay for the m^{th} signal version τ_m is evaluated using the difference of the DVB receiver distances from the closest DVB transmitter, $\vec{D}_{q,m_{\min}}$ and the m^{th} DVB transmitter, $\vec{D}_{q,m}$. Mathematically,

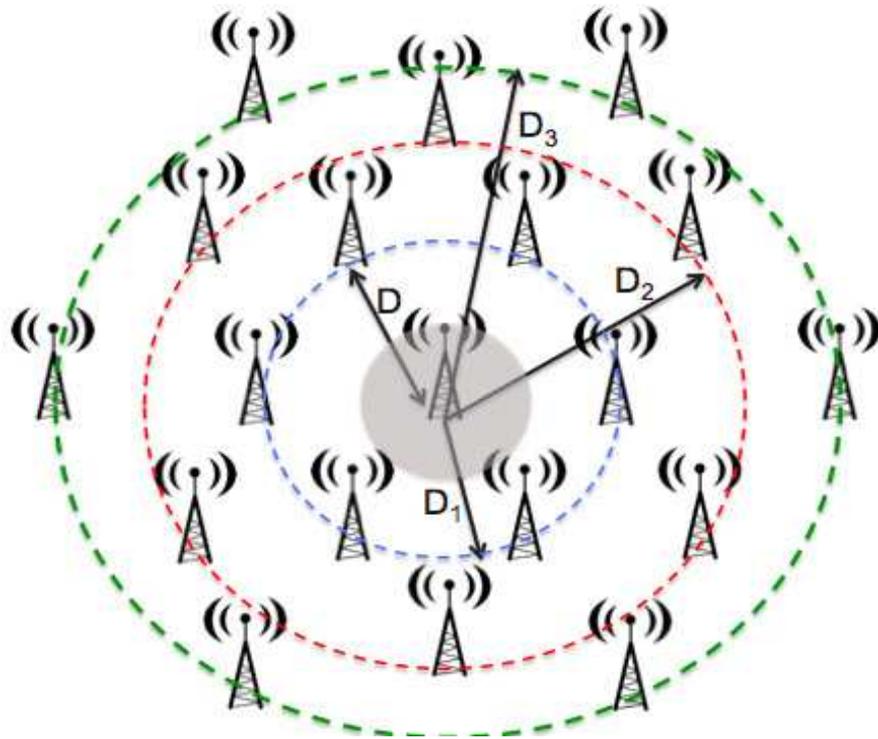


Figure 2.8: Distance of the q^{th} ring, D_q

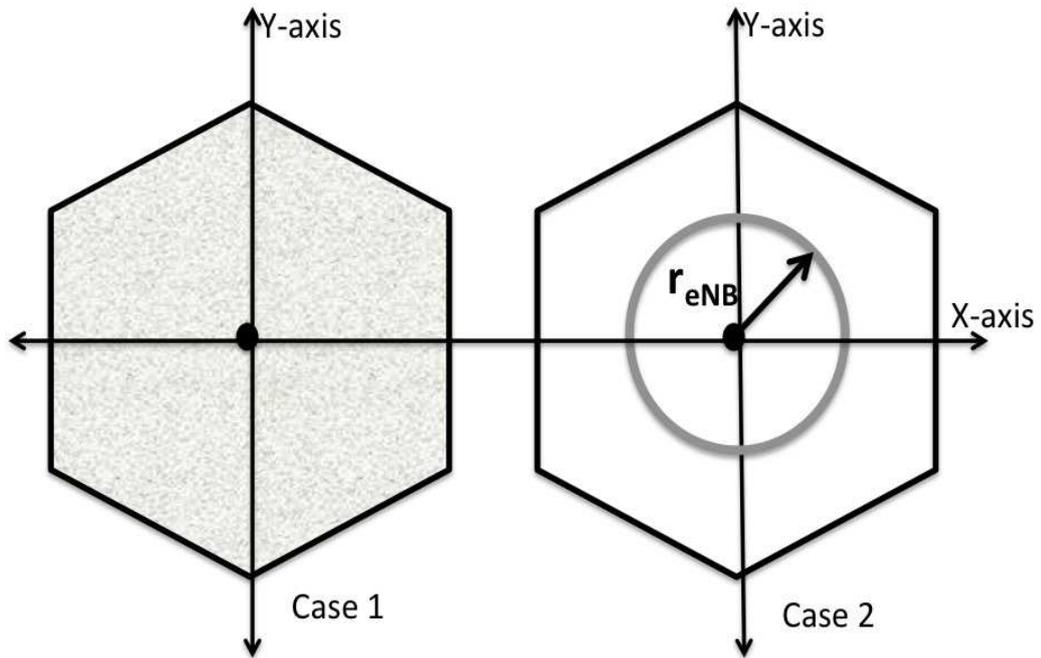


Figure 2.9: Central DVB cell: DVB receivers placement

$$\tau_m = \frac{1}{c} \left(\left| \vec{D}_{q,m} - \vec{r}_{eNB} \right| - \left| \vec{D}_{q,m_{min}} - \vec{r}_{eNB} \right| \right), \quad (2.4)$$

where, c represents the speed of the electromagnetic radiations i.e. 3×10^8 m/s. If cells are assumed to be circular in shape then $\vec{D}_{q,m_{min}} = 0$, as the center of the cell (i.e. central DVB transmitter) becomes the closest point for all the receivers in the central cell. The receivers very close to the central DVB transmitter i.e. $\vec{r}_{eNB} = 0$, experience the most delayed signal versions from any transmitter in the q^{th} ring. Hence, the maximum time delay value from the q^{th} ring is,

$$\tau_{max}^q \approx \frac{1}{c} D_q. \quad (2.5)$$

2.5.2 Propagation Model

Path-loss model

We take the well-known Okumura Hata model as the average path-loss model for the signal propagation in the considered scenario. It is common to apply this model to the DVB networks also e.g.[32]. According to the Okumura Hata model the average path loss in urban environment is given as,

$$\begin{aligned} L_{dB} &= 69.55 + 26.15 \log(f_c) - 13.82 \log(h_t) \\ &+ (44.9 - 6.55 \log(h_t)) \log(r) + 4.97 \\ &- 3.2(\log(11.75h_r))^2, \end{aligned} \quad (2.6)$$

where, r is the distance (in km) between the receiver (i.e. a handheld) and the transmitter, h_t is the transmitter height (i.e. h_{DVB} in meters), h_r is the height of the receiver (in meters) and f_c is the signal's carrier frequency (in MHz).

Shadow fading model

The Shadow fading (also called Large-scale fading or Slow fading) introduces variations in the power level received at the receiver, which is mainly because of the signal getting shadowed through large obstacles like buildings and trees etc. Typically, this variation in the received signal power is modeled by the standard log-normal distribution. We generate a simple map by adding a common and uncommon part for a correlated shadow fading. The standard deviation for the two parts i.e. σ_{cn} and σ_{ucn} respectively,

is given as,

$$\begin{aligned}\sigma_{cn} &= \sqrt{\chi}\sigma, \\ \sigma_{ucn} &= \sqrt{1-\chi}\sigma,\end{aligned}\tag{2.7}$$

where, χ is the correlation coefficient, σ is the standard deviation of the overall signal variation. For outdoors, $\sigma = \sigma_o$, where σ_o is the standard deviation outdoors. For the indoor case,

$$\sigma = \sqrt{\sigma_o^2 + \sigma_i^2},\tag{2.8}$$

where σ_i is the standard deviation for the indoor shadowing.

The standard deviation of the received power level due to shadowing is typically $\sigma_o = 5.5\text{dB}$ [33]. In [34, 33] the typical value given for a site-to-site cross correlation is 0.3- 0.5.

Received Signal and Noise powers

The received power strength for a given distance of the handheld receiver r from the i^{th} DVB transmitter can be evaluated as given in (2.9),

$$P_{s,i} = P_{t,i} - L_T - \xi\sigma + G_{iso} - 10\gamma \log r,\tag{2.9}$$

where, $P_{t,i}$ is the transmission power from the i^{th} source of DVB or LTE network, L_T represents the distance-independent part of the average path loss, G_{iso} is the handheld antenna gain for the given signal, γ is the average path-loss coefficient and ξ is a lognormally distributed random variable. The Noise power, N_0 in dB can be given as,

$$N_0 = kTB + F,\tag{2.10}$$

where, k is the Boltzman constant, B is the signal Bandwidth, T is the thermal noise temperature, F is the Handheld receiver 's Noise Figure.

Earth Curvature and the radio horizon

Given the fact that our earth is an oblate spheroid, for very large distances the radio horizon may get disrupted due to the curvature it has. In our analysis we assume the earth to be a regular sphere of radius, $R_e = 6371$ km. In Figure 2.10 several

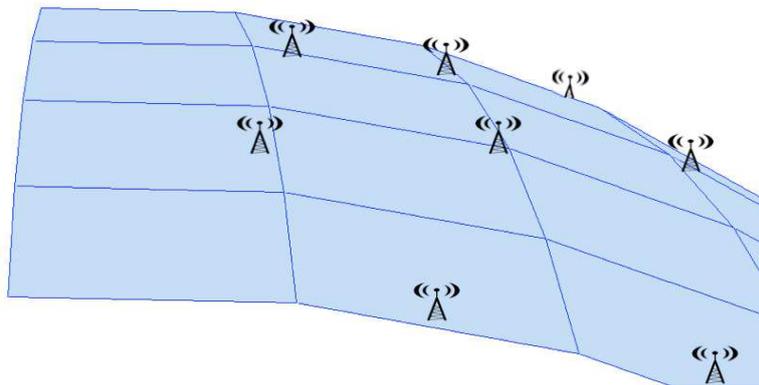
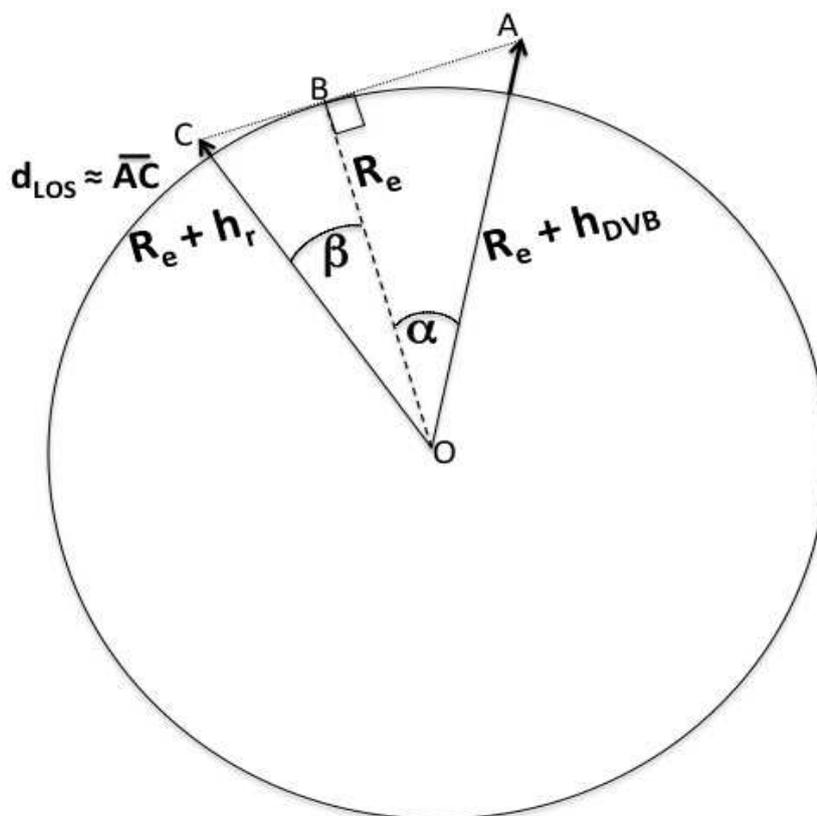


Figure 2.10: DVB Transmitters over Earth 's surface

Figure 2.11: Maximum distance with Line of Sight, d_{LOS}

transmitters are shown which are sufficiently far from one another to experience the curvature in the earth surface.

In Figure 2.11 we take two radial lines from the earth 's centre to a DVB transmitter and a handheld DVB receiver. Let d_{LOS} be the maximum distance till which there is a LOS between the DVB transmitter and the receiver. The $\triangle OAC$ contains two right angled triangles i.e. $\triangle OAB$ and $\triangle OBC$.

In $\triangle OAB$, we know that,

$$\begin{aligned} \sin\alpha &= \frac{\overline{AB}}{\overline{OA}} \\ \alpha &\approx \frac{\sqrt{2R_e h_{DVB} + h_{DVB}^2}}{R_e + h_{DVB}} \end{aligned} \quad (2.11)$$

Geometrically, $d_{LOS} = R_e(\alpha + \beta)$, therefore, d_{LOS} as a function of R_e and the transmitter and receiver heights can be given as,

$$\begin{aligned} d_{LOS} &= R_e \left(\frac{\sqrt{2R_e h_{DVB} + h_{DVB}^2}}{R_e + h_{DVB}} + \frac{\sqrt{2R_e h_r + h_r^2}}{R_e + h_r} \right) \\ d_{LOS} &\approx \sqrt{2R_e h_{DVB}} + \sqrt{2R_e h_r} \end{aligned} \quad (2.12)$$

For the value of DVB transmitter height considered in Table 2.3 i.e. $h_{DVB} = 150$ m, the maximum distance with a Line of Sight (LOS) between the transmitter and the DVB receiver is 48 km⁹. In other words the horizon for signal transmission to a DVB receiver for a given transmitter height of 150 m is 48 km, which narrows down as we reduce the transmitters antenna height.

We consider the **round – earth** model which blocks all signal transmissions to the receiver, for a distance greater than radio horizon i.e. for $r > d_{LOS}$. In our simulations we also have results for the **flat – earth** model which ignores the horizon limitation due to earth curvature.

For a given height of the transmitter and the Inter-site distance there is a limited number of neighboring SFN transmitter rings which can contribute to the SFN transmission. For example, for $D = 50$ km, even the Transmitters from the first ring of the Transmitters can not contribute to all users. On the other hand, for $D = 24$ km, according to Table 2.2 the contributors even from the third ring contribute in the SFN.

2.6 SINR distribution in DVB SFN

We study the SINR distribution in a DVB SFN coverage area. For the major part of the analysis we choose an Inter-site Distance (ISD) close to the practical one [35], but

⁹The radio horizon is calculated to be 48 km for the height of handheld DVB receivers (i.e. $h_r = 1.5$ m), for a fixed DVB receiver it was found to be 55 km given the roof top antenna is 10 m high

Table 2.3: Parametric Values for the SFN

Parameter		Value	Unit
Transmission Power	P_t	80	dBm
Inter-Site Distance	D	24, 31 & 50	km
Guard Interval Fraction	g_{frac}	1/4	-
FFT size		8k	-
Pilot Pattern		PP1	-
Equalization Interval	T_p	$\frac{T_u}{3}$ ¹⁰	-
Modulation & coding		1/2-16 QAM	-
Minimum SINR	S_{min}	9.2	dB
Bandwidth	B	7.77	MHz
Receiver 's height	h_r	1.5	m
Antenna Gain (see [7])	G_{iso}	-7.36	dBi
Transmitter 's height	h_{DVB}	150	m
Carrier Frequency	f_c	650	MHz
Correlation coefficient	χ	0.5	-
Std. Dev. Shadowing outdoor	σ_o	5.5	dB
Std. Dev. Shadowing indoor	σ_i	5	dB
Number of users	n	10000	-

we also include some analytical work for the smaller ISDs. As analysis of SFNs with small ISDs is relevant in the perspective of DVB cells with smaller dimensions getting standardized. Small DVB cells can be essential to improve the handheld coverage.

In this section we discuss the results of our simulations, which were done for the SFN scenario defined in the preliminaries for the simulation work. We consider two kinds of DVB receiver arrangements illustrated as Case 1 and Case 2 in Figure 2.9. The two cases are used to analyze: the *SINR* distribution in the cell area and the *SINR* profile along the cell radius respectively. In Table 2.3 we present the parametric values used in our simulations.

¹⁰We take an FFT size of 8k i.e. $T_u = 896 \mu\text{s}$, with a long GIF $g_{frac} = \frac{1}{4}$ i.e. $T_g = 224 \mu\text{s}$. The 8k FFT size has lesser sensitivity to the doppler effect w.r.t. 16k or 32k. The PP1 pilot pattern should be used for the considered FFT size and GIF combination, Table I.5 of [1]. For PP1 the Nyquist limit is $\frac{T_u}{3}$ for the time-frequency interpolation, which gives an equalization interval of $T_p = 266 \mu\text{s}$.

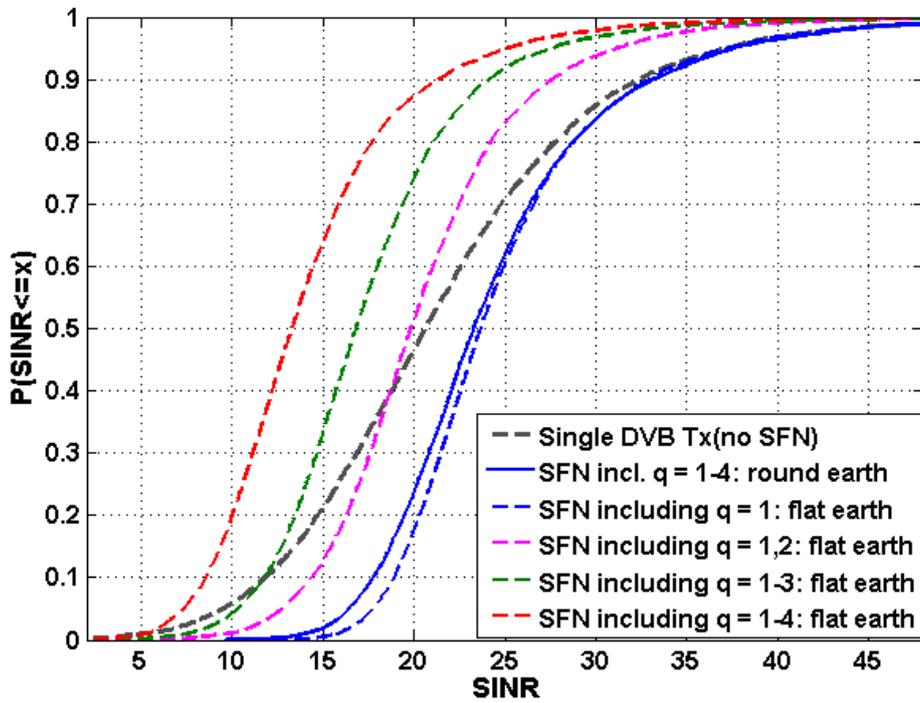


Figure 2.12: CDF of user SINR values for ISD = 50 km

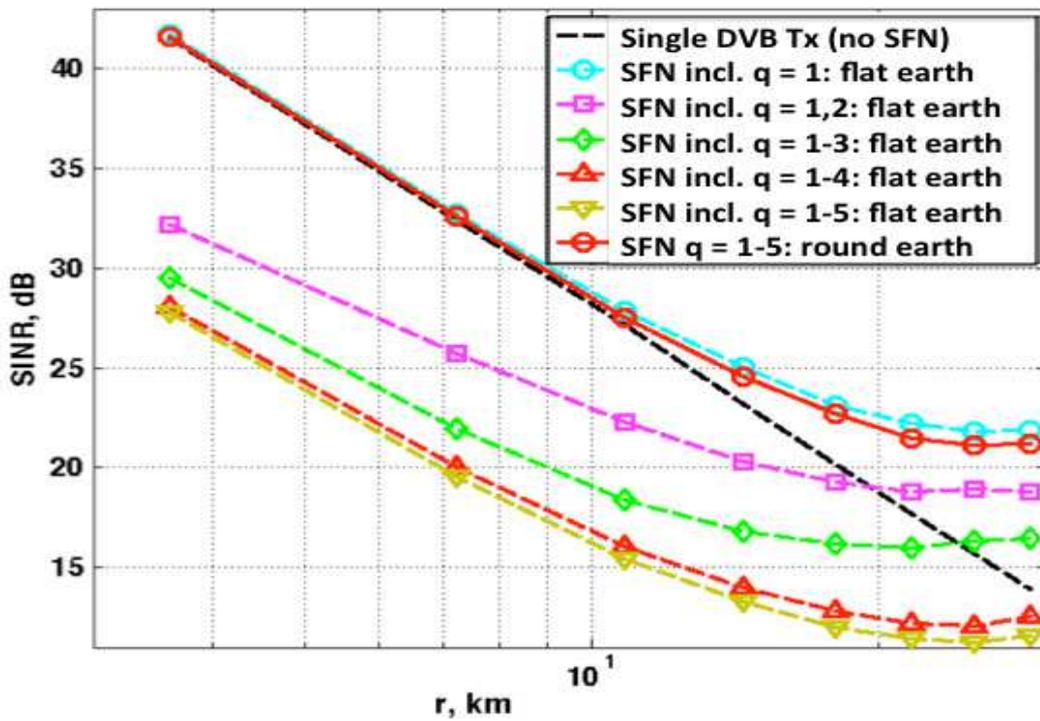


Figure 2.13: SINR vs Distance, for ISD = 50 km and outdoor conditions

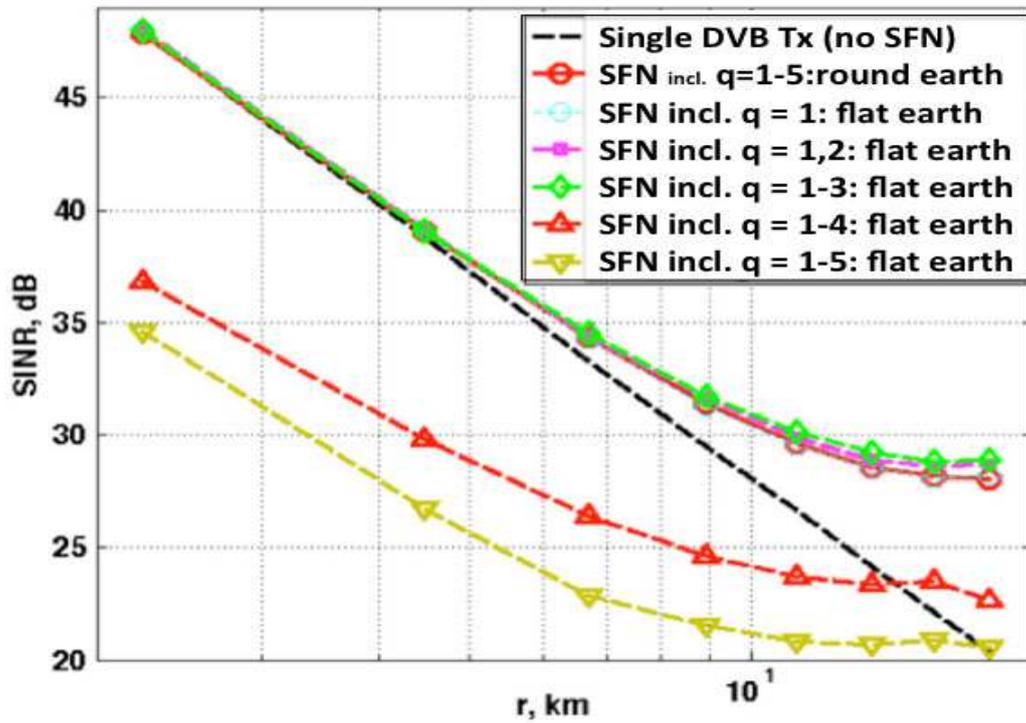


Figure 2.14: SINR vs Distance, for $ISD = 31$ km and outdoor conditions

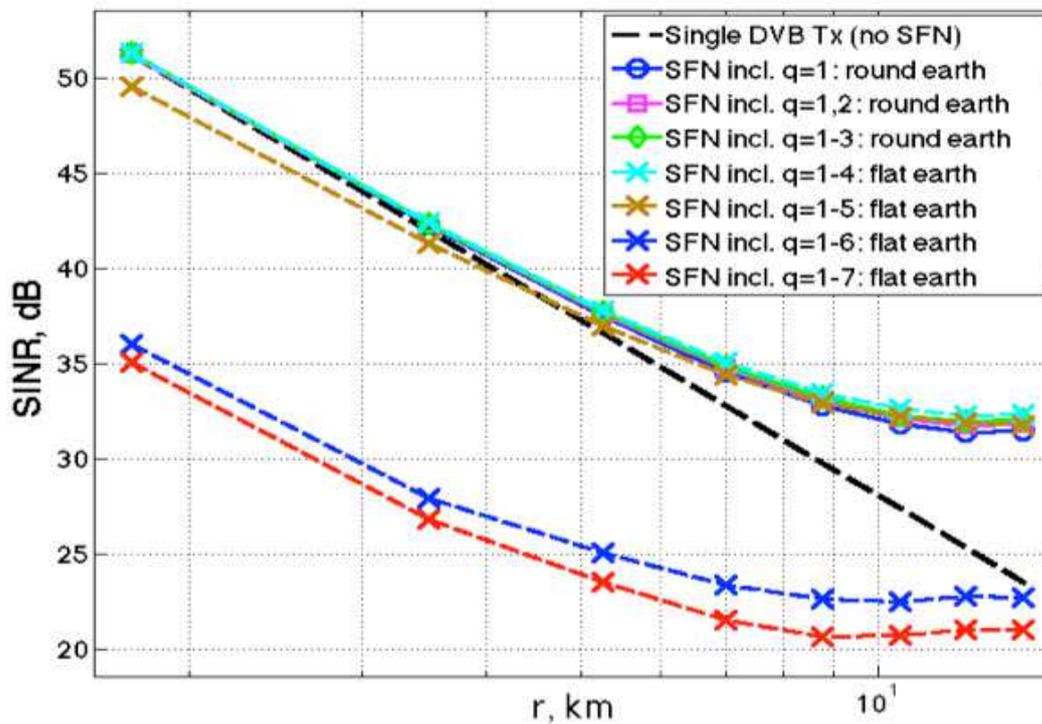


Figure 2.15: SINR vs Distance, for $ISD = 24$ km and outdoor conditions

2.6.1 SINR distribution in the cell area

The first part of the simulation results corresponds to the uniform distribution of DVB receivers in the central cell area (i.e. Case 1 shown in Figure 2.9). In Figure 2.12 we

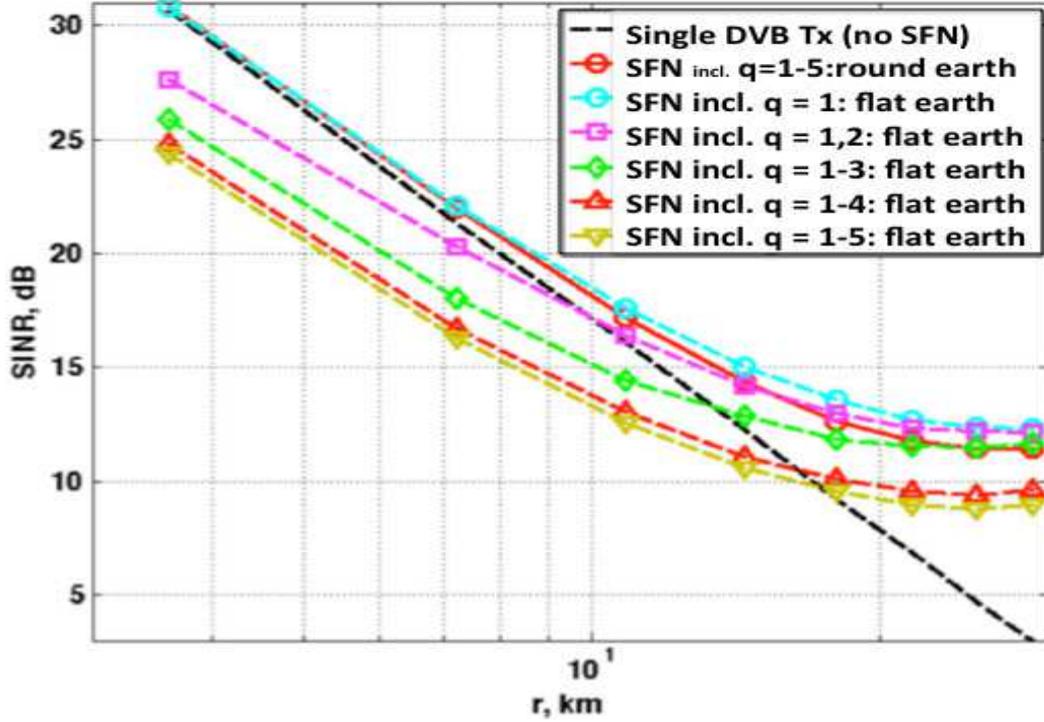


Figure 2.16: SINR vs Distance, for ISD = 50 km and indoor conditions

plot the Cumulative Distribution Function (CDF) for SINR values in the Central cell area. It can be observed that for the flat-earth model, a SFN comprising just the first ring of DVB cells along with central cell gives higher SINR values than SFNs including farther rings also. The DVB SFN coverage is almost 100% for a $\frac{1}{2}$ code rate 64-QAM signal requiring $SINR \approx 13$ dB [7], [36]. The SFN including $q = 1, 2$ i.e. first two rings, performs worse because the transmitters from the 2^{nd} ring produce self-interference for the receivers. For a user very close to the central DVB transmitter, as the 2^{nd} ring's distance $D_2 = 86.5$ km for $D = 50$ km (see (2.3)). This corresponds to $\tau_{max}^q = 288.3 \mu\text{s}$ (see (2.5)) which means that the signal arrives when the equalization interval is over i.e. $T_p = 266 \mu\text{s}$. The SINR values in the Central DVB cell are degraded as we further include the transmitters at farther distances in the SFN e.g. SFN including $q = 1$ to 3 and SFN including $q = 1$ to 4 perform even worse.

The round-earth model curves for all sizes of the SFN coincide because there is no signal transmission for the distances greater than 48 km between the transmitters and receivers. Therefore only the 1^{st} ring shall contribute to a big percentage of the handhels in the central DVB cell for any size of the SFN considered.

In Figure 2.12 we represent the SFN including first four rings. Since there is no transmission beyond the maximum distance of the line of sight, therefore in the round earth model the SINR is same for any number of DVB transmitters' rings included

in the SFN. It should also be noticed that the average $SINR$ for the solid curve is a bit lower w.r.t. the curve for the flat-earth model SFN comprising just 1st ring of the neighboring transmitters. Because the receivers on the cell edge do not benefit from the positive contribution from some neighboring transmitters, which would contribute positively if there was LOS (i.e. $d_{LOS} = 48$ km). Overall a limited radio horizon blocks the strong negative influences from the neighboring cells and comparatively the loss of the positive contribution is small.

We do not observe any self-interference in the SFN for the round-earth model except some minor loss of the positive contribution due to limited radio horizon (i.e. 48 km). For the self-interference to occur, the maximum LOS distance should be wider than 67 km between a transmitter and a handheld receiver. The mentioned distance corresponds to the guard interval duration $T_g = 224$ μ s and a GIF of $\frac{1}{4}$. To increase the system capacity, GI could be shortened. We consider $g_{frac} = \frac{1}{4}$. The next shorter GIF is $\frac{19}{128}$, i.e. $T_g = 133$ μ s for the considered OFDM useful symbol duration. This GI corresponds to 39.9 km distance. In this case a relatively wider radio horizon (i.e. 48 km) allows some Self-interference from the neighboring transmitters. Moreover, for this choice of GIF with 8k FFT size the T2-Lite profile in [1] recommends PP2 or PP3 pilot patterns for which if frequency-time interpolation is used, then $T_p = \frac{T_u}{6}$, which halves the equalization interval and directly reduces the signal strength. Hence, $g_{frac} = \frac{1}{4}$ is a good choice for the considered values of the network parameters in Table 2.3.

2.6.2 SINR profile along the cell radius

In this part of analysis we study the relationship of the $SINR$ with the distance for different ISD values and number of interferers around the central cell. Because of the symmetry of the layout we consider rings of equidistant users for each radial distance (see Case 2 in Figure 2.9). In the plots we consider an average of the $SINR$ values per receiver in each ring and plot it against the given distance from the central transmitter.

In Figure 2.13 the SFN including $q = 1$ ring for the flat earth model has the highest $SINR$ on the edge of the cell. For the bigger SFNs, i.e. SFN including 1-2, 1-3 and 1-4 rings the average $SINR$ reduces due to the increased self-interference. Another important point to be noted is the least $SINR$ value which is not at the cell edge because of the positive contribution from the neighboring transmitters for the edge receivers.

In the case of the round-earth model all sizes of SFN have the same $SINR$ profile as the one for the SFN including just 1st ring of the neighboring DVB transmitters.

Therefore in Figure 2.13 we show the SFN including $q = 1$ to 5, for the round-earth model.

For the round earth model the SINR level of the edge receivers is a bit lower than the SFN including $q = 1$ of the flat earth model, as the limited radio horizon blocks some positive contribution to the SINR of the transmitters.

In Figure 2.14, the ISD is reduced to 31 km. For this ISD, transmitters till the third ring participate positively, therefore, the SFN including $q = 1-3$ gives higher SINR values compared to other SFN sizes, because it is the largest possible SFN with all transmitters contributing positively. From Equation 2.3, the distance for the 3rd ring sites is 62 km, which is smaller than $R_g = 67$ km. Similarly, for $D = 24$ km, even the 4th ring distance i.e. 63.4 km, will be smaller than $R_g = 67$ km. As in Figure 2.15, we can observe the SFN including $q = 1$ to 4 gives higher SINR values than other SFN sizes for the flat earth model.

In Figure 2.15 for the round earth model the SINR profile for all the SFN sizes bigger than $q = 1-3$ coincided, because the D_3 (from Table 2.2) is equal to the radio horizon (i.e. $d_{LOS} = 48$ km) for the considered set of SFN parameters in Table 2.3. In this case the earth curvature blocks the transmission of any self-interference from the farther rings i.e. $q = 5, 6, 7$.

In figure 2.16 we plot the $D = 50$ km case for the indoor conditions. We consider a 11dB penetration loss and $\sigma_i = 5$ dB. Since the penetration indiscriminately weakens both the signal and the interference power and also the noise power is small w.r.t. the self-interference, therefore, the SINR level received for different sizes of SFNs is close unlike the SINR levels for the outdoor receivers.

2.7 Summary

In this chapter we discussed the history of video broadcasting and its digitization to have the dedicated DVB Networks. We presented some of the specific features of the DVB-T2 network, which is an example of state-of-the-art DVB network. We introduced the reader to the system overview, the OFDM modulation architecture and the service specific treatment to the data flows in a modern DVB network i.e. DVB-T2 network.

In this chapter we also emphasized on the concept and properties of a Single Frequency Network, as it enables better spectral efficiency and coverage in the DVB networks. DVB-T2 has a broader set of parameters, therefore we undertook a set of sim-

ulations to study and verify the distribution and the distance-profile of SINR, which is an important link-level parameter in the network planning.

Our analysis on the SFN properties for a DVB-T2 network concludes that SFN enables a higher signal power level for the edge users. It was also observed that the impact of farther DVB transmitters is not small enough to be simply neglected. Specially, for the smaller dimensioned DVB networks it is possible to design large SFNs to enable better coverage and capacity. In the next chapter we analyze the DVB coverage for the handheld receivers and attempt to quantify the link budget losses in terms of the percent-outage for the handheld receivers on-ground.

Handheld Coverage in DVB networks

This chapter concentrates on the handheld receivers' outage problem in a DVB network. We calculate the typical values of the link budget deficits for a handheld receiver in different scenarios. We treat those link budget deficits as the additional losses and determine the respective coverage losses by using two well-known population density models. We also simulate a typical DVB SFN scenario and calculate the DVB service outage for the handheld receivers in the considered SFN network.

In section 3.1 we highlight the history of the handheld reception of a DVB transmission. In section 3.2 we define several cases of the DVB handheld receivers and compare their link budgets with a fixed DVB receiver configuration. We also explain the propagation model for the analytical work. Based on the link budget and propagation configuration, we evaluate the total power deficit for handheld receivers w.r.t. fixed receivers. Section 3.3 explains the fundamentals on the outage in a DVB network. We consider two very well-known population density models for our analysis and derive the formulae of the cell area outage for each model. In section 3.4, we calculate the percent-outage due to the link budget losses for the handheld receivers. We take the link budget losses from section 3.2 and model the link budget deficits of the handheld DVB receivers as additional power losses for a typical fixed DVB receiver with a roof-top mounted antenna. Because of these additional losses, the coverage for the handheld receivers is less w.r.t the fixed receivers.

In section 3.5, we briefly mention about the choice of the propagation models, SFN model, the parametric values and the considered SFN scenario for the simulation work. The mentioned simulations are performed to determine the cell area handheld receivers outage in a SFN which covers fixed DVB receivers. Section 3.6 comprises the simulation result and the followed discussion on it. In section 3.7 we recapitulate our findings regarding the factors responsible for the handheld receivers outage in the DVB networks.

We conclude that there is enough margin to improve the current level of coverage for the DVB handheld receivers.

3.1 DVB standardization for the handheld reception

3.1.1 Global Handheld TV Broadcast business

Just before the beginning of new millennium (i.e. 1999) the handheld reception of digital TV had been attempted. According to [12] the Japanese Integrated Service Digital Broadcast - Terrestrial (ISDB-T) was the first to standardize television transmission to handheld receivers.

In Europe DVB-Handheld (DVB-H) was introduced as an ETSI standard in November 2004, while DVB- Satellite Handheld (DVB-SH) was another solution proposed by DVB. DVB-SH was a hybrid solution by being based on S-band Satellite and Terrestrial networks. According to [13], DVB-SH and DVB-H could not become big successes because of the difficulties faced to fit the business models of the Mobile Network Operators.

In the prologue of [9], the author mentions some reasons for a global failure of the mobile TV. The first reason was the non-unified efforts of the broadcasters and Mobile Network Operators, which ended up mobile operators transmitting 3G unicast streaming, while broadcasters remained restricted to terrestrial transmission of TV programs replication with no interactivity.

In the previous decade specifically in Europe the market was split due to the existence of multiple standards. For example within Germany there were two networks i.e. DMB and DVB-H and both of them were eventually shut down. Further to augment the worries was the unavailability of the spectrum, which stumbled launches in large parts of Europe and Asia. The third reason was a misread from the operators side, who were interested in the pay TV business model despite their observation of the popularity of the free-to-air TV service for the handhelds in Korea and Japan. The limited capabilities of the handheld receivers also contributed to the failure of those sporadic efforts.

3.1.2 Technological Limitations of the handheld standards

High definition multimedia broadcast to the handheld receivers still does not have a proper business model. The reasons have there roots in the technological limitations

which have existed in the past and some of them still impend an efficient broadcast to the handheld receivers. Till this date a number of standards have been proposed but none of these standards has been successful [37]. Those standards include DVB-H, Terrestrial-Digital Multimedia Broadcasting (T-DMB) and DVB-SH etc.

Conventionally, a handheld multimedia transmission has always been multiplexed with the existing terrestrial transmission, over an infrastructure primarily designed for a terrestrial transmission. In the specific case of a DVB-H transmission, the multiplexing scheme forces DVB-H transmission in the same time slot as the DVB-T, thus the DVB-H transmission power is the same as for a DVB-T transmission. This resulted in a reduced coverage for the handheld receivers [38, 39, 40].

Another approach adopted by operators was to have a hierarchical modulation for the DVB-T/H modulators [41]. In this scheme DVB-T/H modulator has two transport streams input, which are high and low data rate versions of the same logical flow. The low data rate version is FEC coded and modulated for a robust modulation scheme and low code rate. The bits from the lower order modulation are embedded with the higher order modulation in the same frame [42]. A better coverage for the handheld receivers receiving a Low definition TV service is achievable, but the overall error performance of DVB-T/H system with the hierarchical modulation is penalized by 10s of dBs compared to a non-hierarchical DVB-T modulator [43].

In [44, 45] authors while commenting on the feasibility of a DVB transmission to the handheld receivers, propose the concept of DVB-H specific infrastructure. The major drawback of this idea is the cost of its deployment. In [39] the author extends his discussion by giving the idea of a marriage between broadcast and the cellular network infrastructures. He proposes the idea of an inter-technological cooperation for an efficient multimedia transmission to the handheld receivers.

3.1.3 State-of-the-art on the Handheld TV Broadcast

According to the design targets laid in [3], DVB-T2 network is supposed to provide services for both fixed and portable receivers [46, 47, 48]. For the portable handheld reception a DVB-T2 system additionally provides a more robust version of the same service in parallel, in a separate PLP (see section 2.2.1).

In the terrestrial application of DVB, the DVB-T2 technology is offering much better capacity and coverage compared to its predecessor. For instance, the capacity available for a 8MHz bandwidth using 256-QAM is 50 Mbps [3]. This capability of transmitting high data rates is a key enabler for 3DTV and HDTV services to be transmitted via

DVB-T2, which can support three 3D services at maximum [49, 50]. However, this capability does not enable DVB-T2 network to provide the same level of coverage to a handheld receiver as enjoyed by a fixed receiver with roof-top mounted antenna. To achieve the same level of coverage a DVB-T2 system is required to compensate the losses in the link budget of a handheld receiver.

A new DVB handheld standard i.e. DVB-Next Generation Handheld (DVB-NGH) is already awaiting [15]. In [51], authors predict DVB-NGH to be close to the DVB-T2 standard and they also realize the need for a denser network for the handheld coverage specially indoors. In [18] also the alignment of the new handheld standard with the state-of-the-art terrestrial network i.e. DVB-T2 is suggested as the first phase of DVB-NGH.

The framing structure of DVB-T2 is capable to efficiently introduce any new service profile. In this regard the Future Extension Frame (FEF) is a special kind of frame reserved within the DVB-T2 framing structure for future use. Exploiting this feature recently a new profile called T2-lite or T2-mobile was introduced in the version 1.3.1 of DVB-T2 ETSI EN 302 755 [26, 1] in July 2011. The T2-lite profile is a subset of the DVB-T2 base profile, exclusively standardized with some additional parametric values for the mobile and portable receivers [18]. In our analysis we take all the parameteric values compliant with the T2-lite profile.

3.2 Handheld Receiver scenarios

We consider two types of DVB receivers: a fixed TV set receiving DVB transmission and a handheld DVB receiver. There can be several possible cases given the situation around the receiver and the kind of signal it receives. For this work we consider three cases, which are:

1. Fixed DVB receiver (receiving a high data rate service)
2. Handheld Outdoor portable DVB receiver
3. Handheld Indoor portable DVB receiver

A pictorial illustration of the considered cases is given in Figure 3.1.

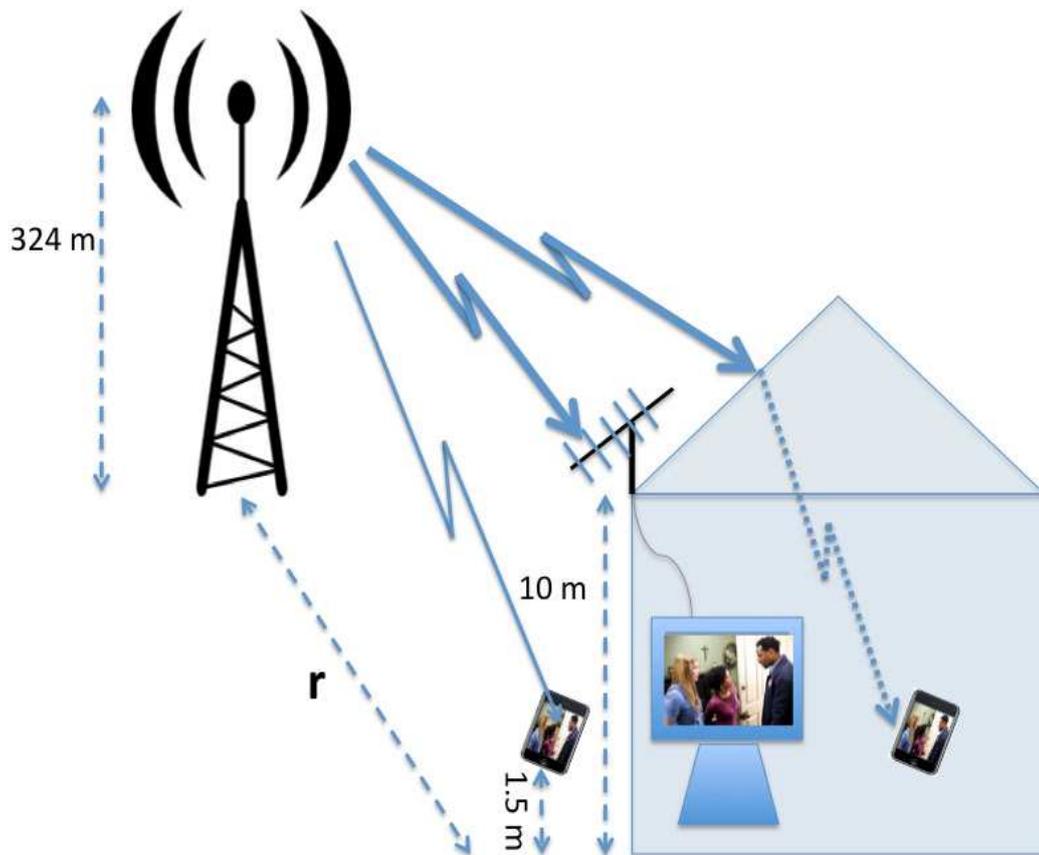


Figure 3.1: Three cases considered for the DVB-T2 reception[2]

3.2.1 Link Budget

The link budget for all of the three cases is shown in Table 3.1. The parametric values are referred from Table 3.3.2 of the technical document 3348 from European Broadcast Union (EBU) [7]. In principle robust and low bit-rate modulation schemes are chosen for the handheld reception to enable good coverage, while high data rates are preferred for a fixed receiver. Therefore, we choose the highest modulation order for the fixed transmission. According to [26], for the T2-Lite profile, the highest permissible modulation order is 64-QAM, for our analysis we choose QPSK.

A fixed DVB receiver has a high gain antenna at the rooftop level. The received signal is fed to the fixed receiver by a lossy feeder cable. In a link budget, such losses are accounted as feeder losses. The handheld receiver has an integrated antenna. As antennae are designed for a reference frequency there is a correction factor which determines the antenna gain value for a given frequency(see (6.4)). In this chapter we consider the typical value of the handheld receiver 's antenna gain, which is -9.5 dBd (or -7.36 dBi) [7].

Table 3.1: Link Budget

Parameters	Symbol	Fixed Roof- top	Portable Handheld			
			Indoor		Outdoor	
Code rate = 1/2		256 QAM	QPSK	64 QAM	QPSK	64 QAM
CNR, dB	C/N	16	3.4	12.8	3.4	12.8
Noise Figure, dB	F	6				
Bandwidth, MHz	B	7.77				
Noise power, dBm	N_0 (see (2.10))	-99.1				
Min. Signal Power, dBm	$P_{s,min} = C/N + N_0$	-82.9	-95.7	-86.4	-95.7	-86.4
Feeder loss, dB	L_f	4	0			
Antenna Gain, dBi	G_{iso}	13.14	-7.36			
Min. Carrier power	$C_m = P_{s,min} + L_f - G_{iso}$	-92.1	-88.4	-78.9	-88.4	-78.9
Additional sig- nal strength for handheld reception, dB	$\Delta C = C_m - C_{m,fix}$	0	3.8	13.1	3.8	13.1

The Carrier to Noise Ratio (CNR) levels taken in Table 3.1 are those which correspond to the Quasi Error Free (QEF) level i.e. a Bit Error Rate (BER) = 10^{-11} [3]. To find those CNR levels we consider BER curves for DVB-T2 Typical Urban-6 taps (TU-6) channel case from [36]. The curves taken had to be extrapolated using a sigmoidal shaped curve-fit till QEF level. (refer to Section 6.3.1 and Appendix B) In the end of Table 3.1 we calculate the additional signal strength required for the handheld reception w.r.t. the fixed roof top reception for each case of the handheld reception.

3.2.2 Propagation Model

We take DVB transmission power $P_t = 73.01\text{dBm}$ (20kW), DVB Frequency, $f_c = 650\text{MHz}$ and the DVB transmitter height, $h_t = 324\text{ m}$ [32]. For the fixed receiver the

signal is received at rooftop level i.e. $h_r = 10\text{m}$. Using Okumura-hata model from (2.6) the average path loss, L_{dB} for the fixed receiver is,

$$L_{dB} = 99.7 + 28.46 \log(r). \quad (3.1)$$

For the handheld receiver, receiver height, $h_r = 1.5\text{m}$, therefore, L_{dB} becomes,

$$L_{dB} = 108.4 + 28.46 \log(r). \quad (3.2)$$

In all cases received power level P can be given as,

$$P = P_t - L_o - 10\gamma \log(r), \quad (3.3)$$

where L_o represents the distance independent part of the average path loss, L_{dB} and γ represents average path loss coefficient. By comparing the coefficients of $\log(r)$ in (2.6) and (3.3) the value for γ is 2.85.

We represent all linear variables by lower case letter symbols, e.g., $p = 10^{\frac{P}{10}}$, $l_o = 10^{\frac{L_o}{10}}$ etc. Hence, the linear version of (3.3) is,

$$p = \frac{p_t}{l_o r^\gamma}. \quad (3.4)$$

The received power level p has variations due to shadowing. This shadowing effect is modeled by taking a standard normal distribution. Hence, p can be modified as,

$$p = \frac{p_t}{l_o r^\gamma} 10^{\frac{\xi\sigma}{10}}, \quad (3.5)$$

where ξ is a random variable defined by the standard normal distribution and σ is the overall standard deviation of the power variation due to shadowing. We represent the standard deviation due to outdoor shadowing by σ_o and the one due to indoor by σ_i . Both of the shadowing effects are uncorrelated therefore the overall standard deviation can be given as, $\sigma = \sqrt{\sigma_o^2 + \sigma_i^2}$. The standard deviation of outdoor shadowing variation is typically $\sigma_o = 5.5\text{dB}$. We take the indoor standard deviation to be $\sigma_i = 5\text{dB}$, for which the overall Standard deviation for the indoor coverage becomes $\sigma = 7.43\text{dB}$.

For indoor coverage signal experiences some penetration loss, L_p , which can be included as an additional distance independent path loss. Thus, the received power level from (3.5) can be given as,

Table 3.2: Total deficit in Power loss for the handheld receivers

	Fixed Roof- top	Portable Handheld			
		Indoor		Outdoor	
Code rate = 1/2	256 QAM	QPSK	64 QAM	QPSK	64 QAM
L_o, dB	99.7	108.4		108.4	
Penetration, L_p, dB	0	11		0	
$L_T = L_o + L_p$	99.7	119.4		108.4	
Configurational deficit, ΔL_T	0	19.7		8.7	
Additional signal strength, ΔC	0	3.8	13.1	3.8	13.1
Total deficit, $\Delta C + \Delta L_T$	0	23.5	32.8	12.5	21.8

$$p = \frac{P_t}{l_T r^\gamma} 10^{\frac{\xi\sigma}{10}}, \quad (3.6)$$

where, $l_T = l_o l_r$, i.e. $L_T = L_o + L_r$ in dB.

Evaluation of Total deficit

The distance independent part of the average path loss, L_o , for the case of rooftop reception is less due to its configurational advantages over the one for handheld receivers i.e. line of sight condition and higher receiver antenna height. We call it the configurational deficit, ΔL_T for the handheld receivers. Moreover, in Table 3.1 we present the additional signal strength needed in the handheld scenario w.r.t. the case of rooftop signal reception for a fixed user i.e. ΔC . In Table 3.2 we give the total deficit in terms of power loss for a handheld receiver with respect to a fixed receiver i.e. $\Delta L_T + \Delta C$, for all the cases considered in Table 3.1.

3.3 Outage in the Cell Area

Because of the presence of shadowing phenomenon the power level received is a random value at a given distance from the transmitter. Using (3.5) the probability of a signal being less than a required minimum signal power c_{min} at a distance r can be given as,

$$\begin{aligned}
\epsilon(r) &= \Pr(p \leq c_{min}), \\
\epsilon(r) &= \Pr\left(\frac{p_t}{l_T r^\gamma} 10^{\frac{\xi\sigma}{10}} \leq c_{min}\right), \\
\epsilon(r) &= \Pr\left(\xi \leq \frac{1}{\sigma} (C_{min} + L_T + 10\gamma \log(r) - P_t)\right),
\end{aligned} \tag{3.7}$$

where $C_{min} = 10 \log c_{min}$ and $P_t = 10 \log p_t$.

The probability considered in (3.7) is basically the outage of the service at a given distance r , denoted by $\epsilon(r)$. For any random variable, X , defined by the standard normal distribution, $\Pr(X \leq x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{u^2}{2}} du = \frac{1}{2} \left(1 + \operatorname{erf}\left(\frac{x}{\sqrt{2}}\right)\right)$. As ξ is also defined by the standard normal distribution, therefore (3.7) can be given as,

$$\epsilon(r) = \frac{1}{2} \left(1 + \operatorname{erf}\left(\frac{C_{min} - P_t + L_T + 10\gamma \log(r)}{\sigma\sqrt{2}}\right)\right), \tag{3.8}$$

In Figure 3.2, using (3.8) the outage probability as a function of the distance is plotted for a single user. For the outdoor and ordinary indoor cases the DVB service outage is plotted for the 1/2-QPSK modulation scheme. It can be observed that a possible cell radius for a 95% coverage is 96 km for the fixed receiver, whereas it is one-third of it for an outdoor handheld. For the case of indoor it is under one tenth value of the fixed receiver coverage.

Because of the shadowing, there exist some outage probability in every part of the cell area. Therefore, the outage has to be analyzed for the entire cell. Whereas, the outage probability considered in (3.8) is for a single user at a certain distance r from the DVB transmitter.

Choice of a radius is always a trade-off between the average power level planned to be received on the cell edge and the edge outage probability. For an operator the transmission power is very important from economic perspective. For a cell radius R there is an average power level, c_{plan} , which operators plan for the edge of the cell. This power level can be represented as,

$$c_{plan} = \frac{p_t}{l_o R^\gamma}. \tag{3.9}$$

We present the received power level at any position in the cell area by combining (3.5) with (3.9) as,

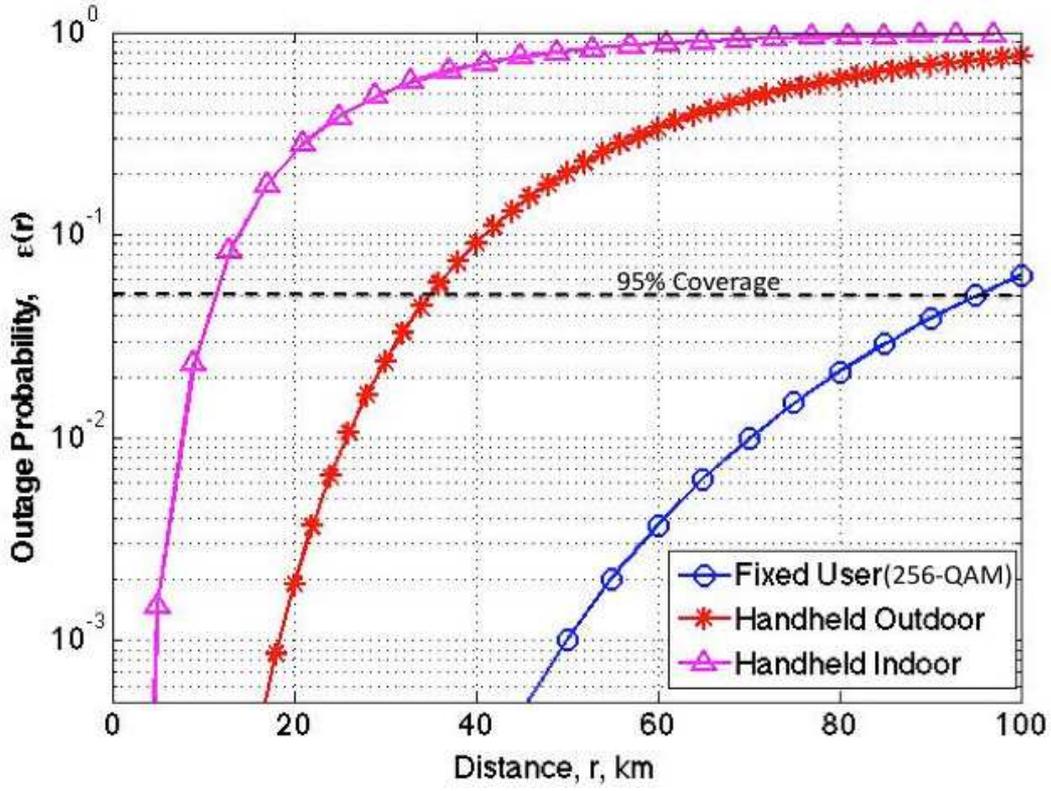


Figure 3.2: Comparison of the outage at a given distance

$$p = \frac{R^\gamma}{r^\gamma} c_{plan} 10^{\frac{\xi\sigma}{10}}. \quad (3.10)$$

Using (3.10) the outage probability can be given as,

$$\epsilon(r) = \Pr \left(\xi \leq \frac{10}{\sigma} \log \left(\frac{c_{min}}{c_{plan}} \right) + \frac{10\gamma}{\sigma} \log \left(\frac{r}{R} \right) \right). \quad (3.11)$$

Using (3.11), (3.8) can be rewritten as,

$$\epsilon(r) = \frac{1}{2} \left(1 - \operatorname{erf} \left(b_1 (C_{plan} - C_{min}) - b_2 \ln \left(\frac{r}{R} \right) \right) \right), \quad (3.12)$$

where $b_1 = \frac{1}{\sigma\sqrt{2}}$, $b_2 = \frac{10\gamma}{\sigma \ln(10)\sqrt{2}}$ and $C_{plan} = 10 \log(c_{plan})$. The Outage probability for the whole cell is averaged over the entire population inside the cell. The average outage probability for the users in a circular shaped DVB cell (i.e. surface area, $s = \pi r^2$) can be evaluated as,

$$\epsilon_s = \frac{\int \int_s \epsilon(r) \rho(r, \theta) r dr d\theta}{\int \int_s \rho(r, \theta) r dr d\theta}, \quad (3.13)$$

where $\rho(r, \theta)$ is the population density function of the cell and θ is the azimuth angular position of a user in the cell w.r.t. the transmitter at the origin. This approach is similar to Jakes' work in [52] but we extend it by considering the average outage for different population density models.

3.3.1 Smeed's Urban Population density

R. J. Smeed proposed to model Urban population density as a direct function of distance in his analysis of the routing systems for the traffic in downtown areas [53]. We take a similar mathematical form to define the population density of a disk-like shaped DVB-T2 cell, with R being the cell radius as,

$$\rho(r, \theta) = \frac{(i+2)N}{2\pi R^{i+2}} r^i, \quad (3.14)$$

where N is the total number of users in the cell and i is a number, such that $i > -2$. Since the Smeed's model relates the population density with the radial distance from the centre. Thus, the number of users as a function of the distance, r can be given as,

$$\begin{aligned} N(r) &= \int_0^{2\pi} \int_0^r \rho(\nu, \theta) \nu d\nu d\theta \\ &= N \left(\frac{r}{R} \right)^{i+2} \end{aligned} \quad (3.15)$$

In Figures 3.3, 3.4 and 3.5 we present the location maps of the DVB receivers for $i = -1.8, 0, 4$ respectively. The DVB Cell centre is at the origin. It can be observed that for $i = 0$ there is a uniform population distribution. For all the positive values of i the receiver's population is higher on the edges (see Figure 3.5 for $i=4$). On the contrary for negative values of i (see Figure 3.3 for $i = -1.8$), most of the receivers are concentrated in the center of the cell.

After several computational steps using (3.12), (3.14) and (3.13), the cell outage probability derived for the Smeed's population density is given as,

$$\begin{aligned} \epsilon_s &= \frac{1}{2} (1 - \text{erf}(b_1 M)) \\ &- \frac{1}{2} e^{\frac{(i+2)^2 + 4b_1 b_2 M(i+2)}{4b_2^2}} \left(1 - \text{erf} \left(b_1 M + \frac{i+2}{2b_2} \right) \right), \end{aligned} \quad (3.16)$$

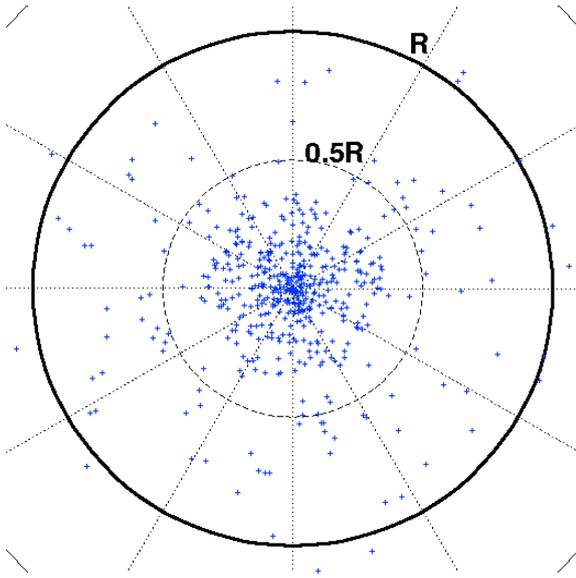


Figure 3.3: Smeed Population distribution for $i = -1.8$

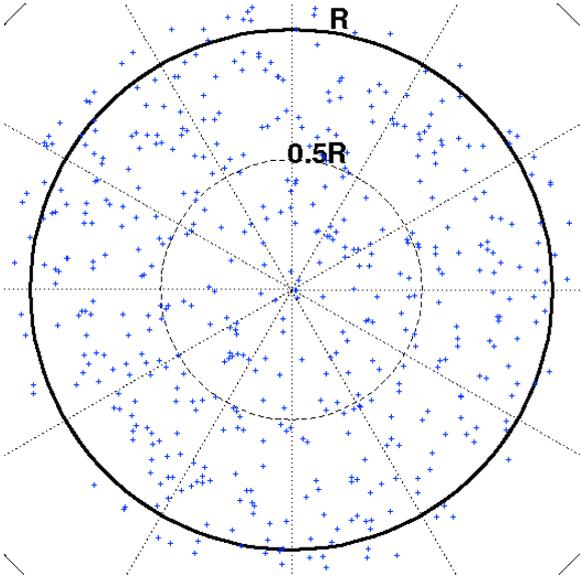


Figure 3.4: Smeed Population distribution for $i = 0$

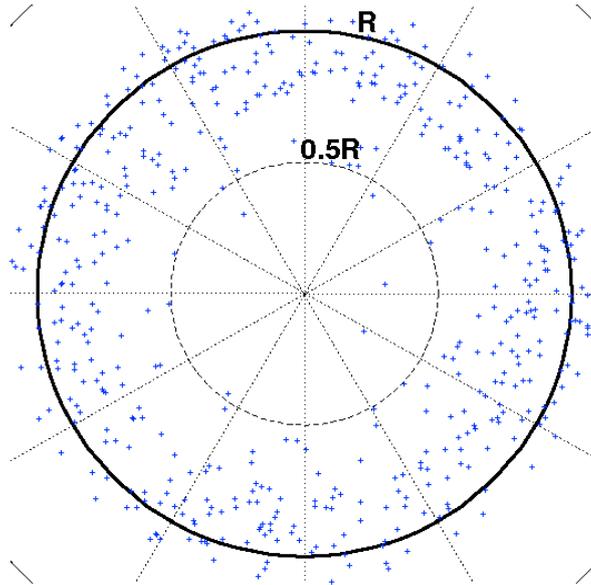


Figure 3.5: Smeed Population distribution for $i = 4$

where, $M = C_{plan} - C_{min}$, is the coverage margin. For detailed computational steps refer to Appendix A.1.

3.3.2 Clark's Urban population density

According to Colin Clark's work on urbanization [54], an urban population density is an exponentially decaying function of the distance from the metropolitan center. As

given in [55] the Clark population density at a given distance is,

$$\rho(r) = \rho_0 e^{-br}, \quad (3.17)$$

where $\rho(r)$ is the residents population density at a given distance, ρ_0 is the population density in the city center and b is the decay parameter. We assume a disk-like circular shape for the cell and in our example the DVB transmitter is in the center of the city, like in [32], thus r is the radial distance of a DVB receiver from the transmitter. At $r = R$ we have the cell edge density, ρ_e , which can be related to R as,

$$bR = \ln \left(\frac{\rho_0}{\rho_e} \right). \quad (3.18)$$

In Figures 3.7 and 3.6 we illustrate the exponential population distribution in the cell for $\frac{\rho_0}{\rho_e} = 10$ and 1.01 respectively.

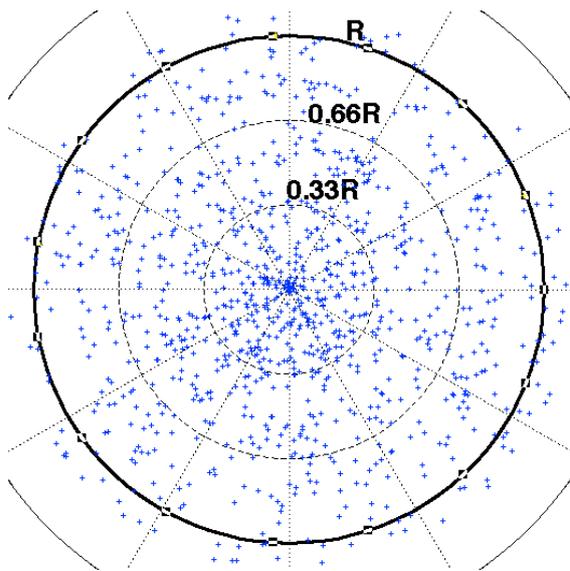


Figure 3.6: Clark's Population distribution for $\frac{\rho_0}{\rho_e} = 1.01$

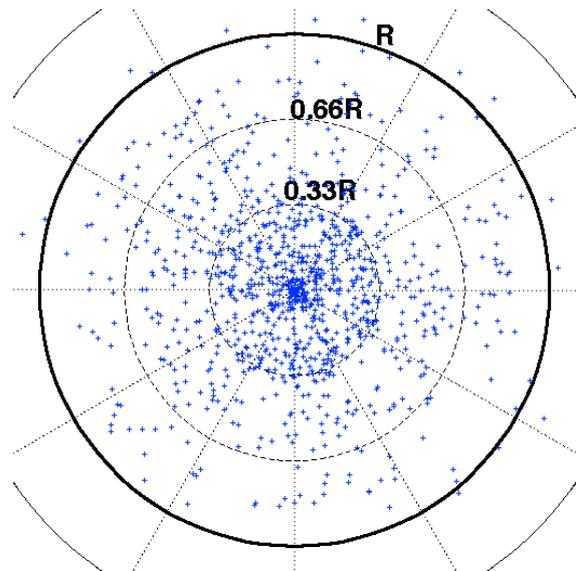


Figure 3.7: Clark's Population distribution for $\frac{\rho_0}{\rho_e} = 10$

For our analysis of a Clark's population density based cell the normalized population density considered is given as,

$$\rho(r, \theta) = \frac{Nb^2}{2\pi(1 - e^{-bR}(1 + bR))} e^{-br}, \quad (3.19)$$

where N is the total number of users inside the cell and R is the cell radius. The number of users as an exponential function of the distance r can be given as,

$$\begin{aligned} N(r) &= \int_0^{2\pi} \int_0^r \rho(\nu, \theta) \nu d\nu d\theta \\ &= N \left(\frac{1 - e^{-br}(1 + br)}{1 - e^{-bR}(1 + bR)} \right). \end{aligned} \quad (3.20)$$

To find the average cell outage probability we solve the integrals of (3.13) with (3.19) and (3.12). The exponential function of (3.19) is expanded using Taylor series i.e. $e^{-br} = \sum_{j=0}^{\infty} \frac{(-br)^j}{j!}$. This form of Clark's exponential population density is computationally similar to the Smeed's model. Thus, the outage probability obtained using the Clark's urban population density model is,

$$\epsilon_s = \frac{1}{2} \left(1 - A \sum_{j=0}^{\infty} B_j (\text{erf}(b_1 M) + C_j) \right), \quad (3.21)$$

where,

$$\begin{aligned} A &= \frac{\left(\ln \left(\frac{\rho_o}{\rho_e} \right) \right)^2}{1 - \frac{\rho_e}{\rho_o} \left(1 + \ln \left(\frac{\rho_o}{\rho_e} \right) \right)}, \\ B_j &= \frac{\left(\ln \left(\frac{\rho_e}{\rho_o} \right) \right)^j}{(j+2)j!}, \\ C_j &= e^{\frac{(j+2)^2 + 4b_1 b_2 M(j+2)}{4b_2^2}} \left(1 - \text{erf} \left(b_1 M + \frac{j+2}{2b_2} \right) \right). \end{aligned}$$

The above equation is obtained after the parametrization of the results with (3.18) to achieve a more intuitive form. Details of the computations for this derivation can be found in Appendix A.2.

In Figure 3.8 we present the Outage probability curves for Clark's Population density on ground, for different values of $\frac{\rho_o}{\rho_e}$. We consider the uniform population density case from Smeed's model i.e. $i = 0$, which coincides with the Clark's model curve for $\frac{\rho_o}{\rho_e} = 1.01$. Although the summation in (3.21) does not change significantly beyond the seventh term of Taylor series expansion, we consider upto 20^{th} term to plot service outage in Figure 3.8. For a higher density ratio a reduction in the outage can be observed.

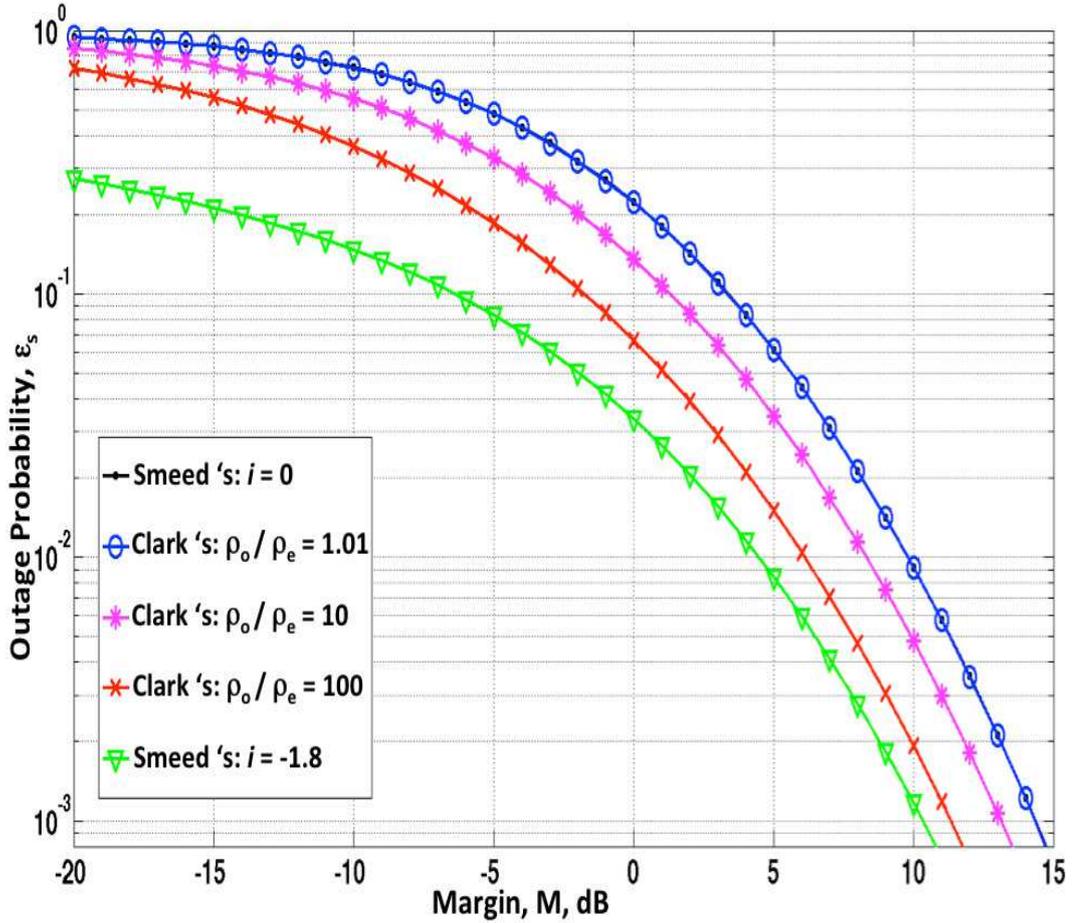


Figure 3.8: Outage probability curves

3.4 Coverage Analysis of the two population density models

Clark's model is a close-to-reality population density model widely used and applied in wireless communications e.g. in [55]. For Clark's model we have taken a density function for $\frac{\rho_o}{\rho_e} = 10$, which is very optimistic. For an analysis of the Smeed's model we take $i = 0$ i.e. the uniform population density and $i = -1.8$ i.e. an ideal case (as for $i = -2$, $\epsilon_s = 0$, see (3.16)).

Graphically, against a target outage (e.g. 0.01, 0.001) planned for the roof-top mounted antenna fixed DVB users in the cell, the dB Margin, $M = C_{plan} - C_{min}$ can be taken from Figure 3.8. In Table 3.2 total deficit of a handheld receiver link budget can be found with respect to the fixed roof-top DVB receiver. The value of M for handheld DVB user is lower because of that deficit, which gives a higher outage in Figure 3.8 i.e. a reduction in the coverage.

Table 3.3: Handheld receivers in Smeed 's population density

Sigma, σ, dB	i	fixed Cov., %	$\Delta L_T + \Delta C$, dB	Handhelds Cov., %	Handhelds Uncovrd, %
5.5 (Outdoor Handheld)	-1.8	95	12	80	15
		99	12	88	11
	0	95	12	50	45
		99	12	72	27
7.43 (Indoor Handheld)	-1.8	99	24	74	25
			36	61	38
		99.9	24	80	19.9
			36	67	32.9
	0	99	24	15	84
			36	2	97
		99.9	24	30	69.9
			36	7	92.9

Table 3.4: Handheld receivers in Clark's population density for $\frac{\rho_o}{\rho_e} = 10$

Sigma, σ, dB	fixed Cov., %	$\Delta L_T + \Delta C$, dB	Handhelds Cov., %	Handhelds Uncovrd, %
5.5 (Outdoor Handheld)	95	12	53	42
	99	12	74	17
	99.9	12	88	11.9
7.43 (Indoor Handheld)	99	24	28	71
		36	6	93
	99.9	24	44	55.9
		36	9	90.9

In Tables 3.3 and 3.4 we have listed several fixed users' percentage coverages. Against each fixed user coverage the graphically obtained reduction in the coverage for handheld users is tabulated. From Table 3.2 we have taken the cases of QPSK outdoor ≈ 12 dB, QPSK Indoor/ 64-QAM Outdoor ≈ 24 dB and 64-QAM Indoor ≈ 36 dB, which represents the case of a high data rate signal indoor reception.

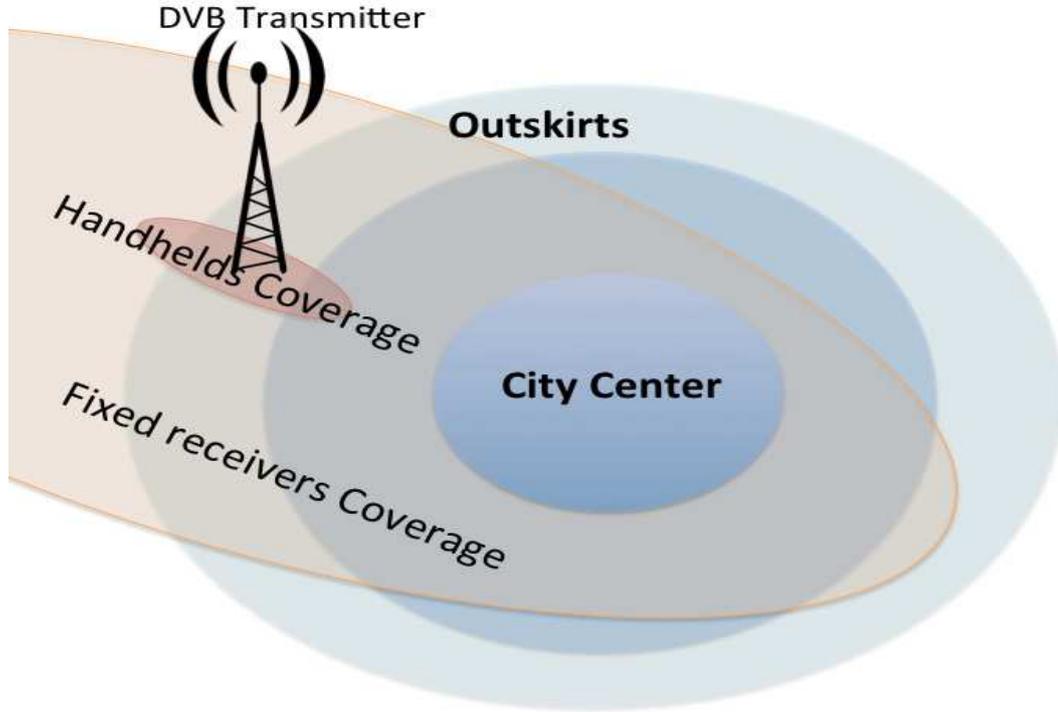


Figure 3.9: DVB-T2 coverage and Urban Population density

In Tables 3.3 and 3.4, we can see that the coverage for the indoor users is reduced by 80-90% even for the strongest modulation and code rate i.e. 1/2-QPSK. In Table 3.2 the deficit for outdoor 64QAM is 22 dB, which is almost the same as the Indoor QPSK i.e. 24 dB. Hence, for the case of higher order modulation the coverage for outdoor handheld is as bad as for the Indoor case.

One possible solution is to add a separate antenna receiving DVB-T2 transmission, which would reduce losses by 9 dB [7], by avoiding the loss due to negative gain of the integrated antenna considered in our analysis. But there are still going to be cases like, 64-QAM in indoor, for which the reduced $\Delta L_T + \Delta C = 33 - 9 = 24\text{dB}$, which is the same as having QPSK indoor e.g. it gives a 71 % coverage reduction in Clark's model in Table 3.4.

In [18], it is mentioned that some advanced techniques like MIMO and TFS (Time Frequency Slicing) are going to be employed in the upcoming DVB-NGH profile to improve Time, frequency and space diversity. In [20] a 4x2 MIMO has been applied to DVB-T2, which shows some improvement of around 5 dB.

We consider a very special case with a tower of several hundreds of meters high in the city center. Normally, it is hard to have such a tall tower in a congested downtown. The tower is generally located outside the city and the radius of a DVB cell, covering

the fixed users only, is very large to achieve a good coverage till the heart of the city (refer to Figure 3.2). Now if we apply the theory of urbanization [54] to a DVB transmitter based in the outskirts, it suggests long distances for most of the handheld receivers from the transmitter, as most of them are cluttered in the city center.

In Figure 3.9 the darkest circle signifies the highest concentration of population in the city center, which means major percentage of the total handheld receivers is in the city center.

In terms of the Smeed's model, this scenario is close to the case of $i > 0$ and for the Clark's model it would correspond to the case of $0 < \frac{\rho_o}{\rho_e} < 1$. The cell area coverage observed for the uniform density model is already very low for indoor and outdoor handheld receivers. For positive values of i or for a fractional value of $\frac{\rho_o}{\rho_e}$, it is going to be even lower. Hence keeping in view a very bad coverage even with very optimistic assumptions, it can be said that the handheld coverage with the existing DVB-T2 infrastructure is going to be worse.

3.5 Handheld receivers in a DVB SFN

3.5.1 SFN Scenario and the parametric values

We consider a uniform population of n handheld DVB receivers and n fixed receivers in a DVB cell. In the centre of the cell there is a DVB transmitter which forms a SFN with the first ring of the neighboring transmitters equidistant from the centre. In Figure 3.10 an illustration of the discussed scenario is depicted. In this analysis we take an ISD equal to the maximum LOS distance for the fixed receivers, which is found to be 55 km (see (2.12)) for the parametric values presented in Table 3.5.

3.5.2 Signal Propagation

In the simulation work we consider the Okumura-hata as the average path loss model (see (2.6)). The signals are considered to be attenuated by a correlated shadow fading (see (2.7)). Moreover, we take the SFN model as described in section 2.3.2.

⁰includes the feeder losses in the cable i.e. 4 dB[7]

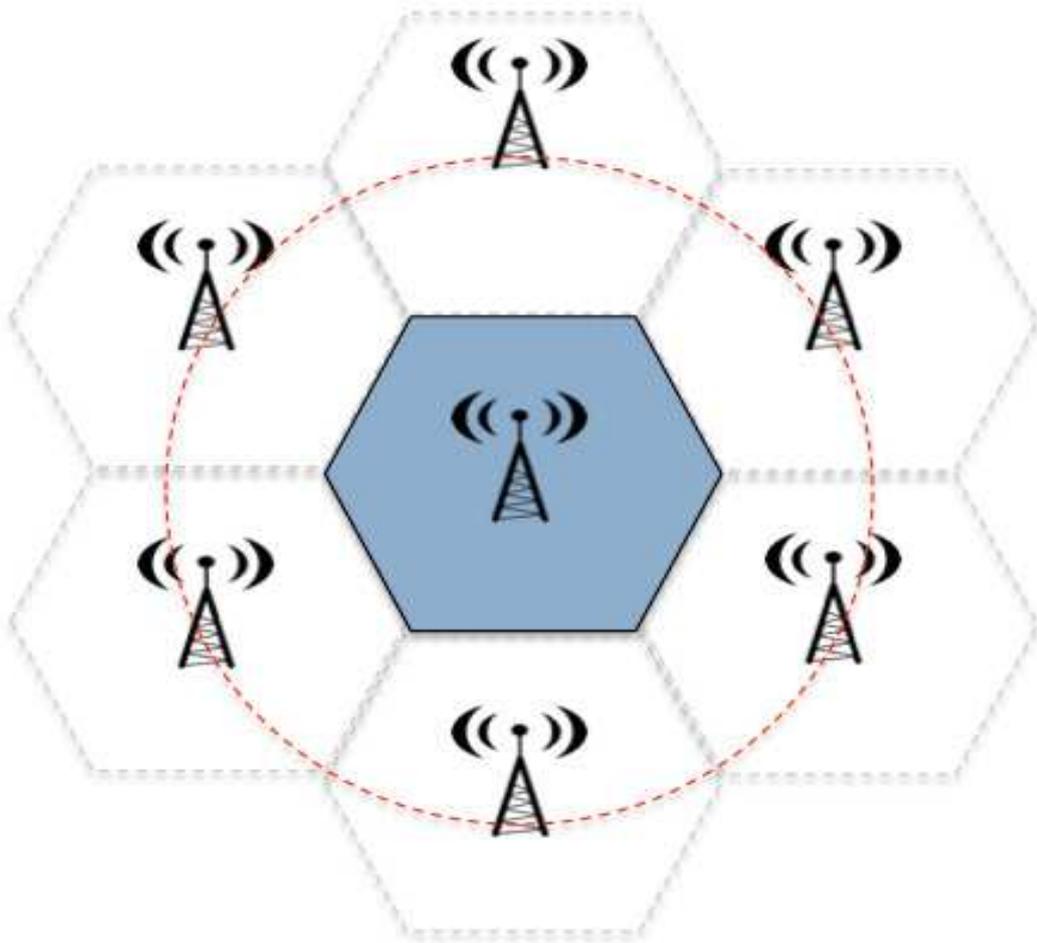


Figure 3.10: A DVB-T2 SFN designed to cover fixed receivers

3.6 Simulation Results

We consider a DVB transmission power of 61 dBm which ensures a 99% coverage for the n fixed users in the DVB cell. As presented in Table 3.5 we transmit a high data rate service for the fixed receivers which is carried by a 256-QAM modulated signal. Compared to this we consider a robust constellation i.e. 16-QAM to transmit the handheld service, which is optimal from both the capacity and the coverage point of views.

For the handheld receivers we take a GIF = $\frac{1}{4}$, which is the largest possible value. The reason to have a large GIF is to ensure a longer duration for the signal recombination, which directly affects the signal strength. We take the maximum FFT size (i.e. 32k) for the OFDM signal intended for the fixed receivers. This ensures a better capacity for the fixed receivers. We choose 8k FFT size for the signal intended to be received by a handheld receiver. As a bigger FFT size makes OFDM signal prone to

Table 3.5: Parametric Values

Parameter		Handheld	Fixed	Unit
Transmission Power	P_t	61		dBm
Inter-Site Distance	D	55		km
Guard Interval Fraction	GIF	1/4	1/16	-
FFT size		8k	32k	-
Pilot Pattern		PP1	PP2	-
Equalization Interval	T_p	$\frac{T_u}{3}$	$\frac{T_u}{6}$	-
Modulation & coding		1/2-16 QAM	1/2-256 QAM	-
Minimum SINR	$SINR_{min}$	9.2	18.9	dB
Bandwidth	B	7.77		MHz
Receiver 's height	h_r	1.5	10	m
Antenna Gain (see [7])	G_{iso}	-7.36	13.14	dBi
Feeder losses (see [7])	G_{iso}	0	4	dB
Transmitter 's height	h_{DVB}	150		m
Carrier Frequency	f_c	650		MHz
Correlation coefficient	χ	0.5		-
Std. Dev. Shadowing outdoor	σ_o	5.5		dB
Std. Dev. Shadowing indoor	σ_i	5	-	dB
Number of users	n	10000		-

errors due to the doppler shift, because of the narrow inter-sub-carrier spacing. In order to have fair comparison we ensure same guard interval for the fixed receivers by taking $GIF = \frac{1}{16}$, as a 32k OFDM symbol duration is four times longer w.r.t. the 8k OFDM symbol duration [1, 3, 7]. All parameters for the handheld receiver are T2-lite compliant [1].

In order to be considered as covered a receiver must have a SINR value higher than the minimum SINR value $SINR_{min}$ required for an error free transmission. Since the $SINR_{min}$ values required for the two kinds of receivers are different, therefore, to have a common point of reference for both cases we define the term $SINR$ -Margin i.e. $Margin = SINR - SINR_{min}$.

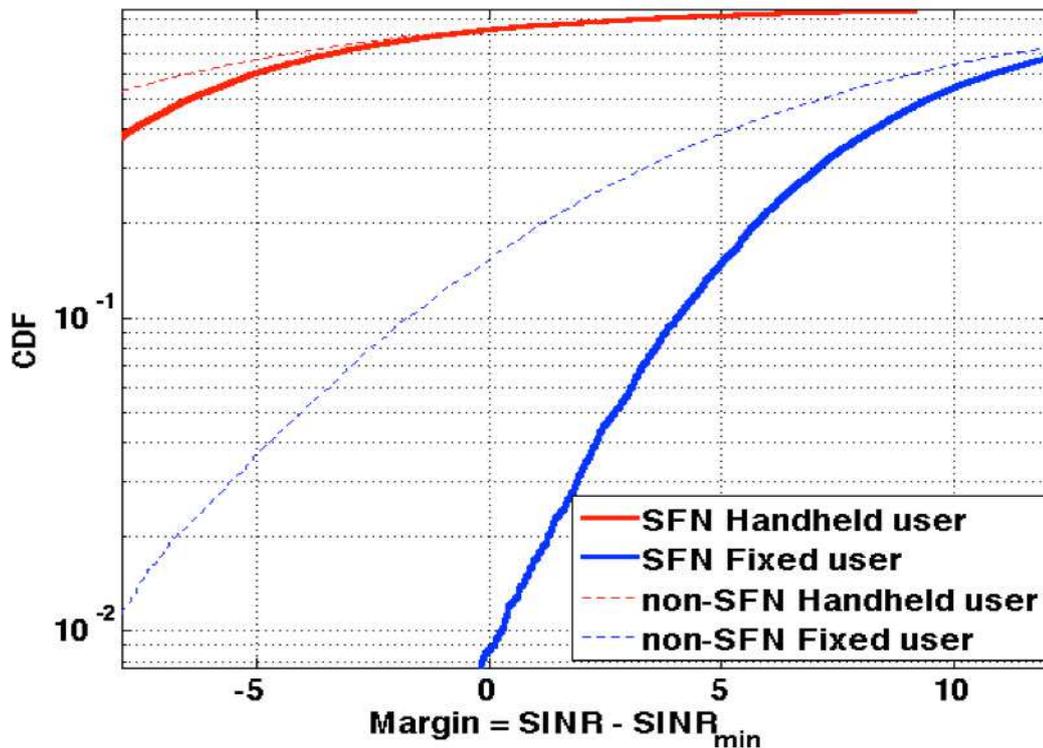


Figure 3.11: Fixed vs Handheld receiver coverage in a SFN

In Figure 3.11 we plot the cumulative probability distribution of the SINR values (i.e. $\text{Prob}(SINR < x)$) also called Cumulative Distribution Function (CDF) for both the handheld and the fixed receivers in the central DVB cell (the colored cell in Figure 3.10) for the SFN and non-SFN cases. In the non-SFN, we consider just one DVB transmitter in the central cell.

The SFN CDF for the fixed receivers shows 99% of the users receiving a Margin value above zero, which means a $SINR$ value higher than $SINR_{min}$, hence, a 99% coverage for the fixed users in the SFN. We observe almost 85% fixed users are covered if there is just a single transmitter in the center of the central DVB cell if the rest of the parameters have the same values. In comparison we observed that only 20% of the handheld receivers have a $SINR$ higher than the $SINR_{min}$ for both the SFN and non-SFN case. Thus we infer that a DVB network designed to cover fixed receivers should allow high margins on SINR if the network is expected to cover the handheld receivers as well.

3.7 Summary

In this chapter we analyze the bottlenecks of a DVB network to ensure an efficient DVB service for the handheld receivers. We started by epitomizing the retrospective efforts rendered by the standardization bodies and other stakeholders to make the DVB transmission to the handhelds a technological as well as a commercial success. We then presented the state-of-the-art on the DVB networks covering handheld receivers. Some of the major contributions of this chapter are: the definition of different handheld scenarios, the calculation of the typical link budget deficits for the respective scenarios, the representation of link budget deficits as the additional losses and the approximate translation of those additional losses into the DVB service outage for the handheld receivers. The DVB service outage for the handheld receivers were derived for two well-known population density models i.e. Clark's model and Smeed's model.

Another part of this chapter is devoted to the handheld reception in a DVB SFN. We used the SFN model, the propagation model and other preliminaries from Chapter 2. We considered a typical DVB SFN designed to cover the fixed users only. The evaluation of the coverage for the handheld receivers reveals similar results as determined by analyzing the outage models derived for the Clark's and the Smeed's population density models.

We observed that the handheld receivers suffer serious coverage problems because of their link budget deficits. We emphasize on the fact that to cover the handheld receivers via a terrestrial unidirectional broadcast network some additional methods are required to be deployed. In this regard cooperation with a pre-existing bidirectional network (like Cellular network) is a promising solution. In the following chapters we explore this idea in detail. In order to make the two technologies cooperate it is important to study their state-of-the-art framing structures. Therefore, in Chapter 4 we present a brief study about the framing structures of a DVB-T2 signal.

4

DVB-T2 Frame Structures

The DVB-T2 technology introduces some new concepts for a more reliable multimedia broadcast. These novel concepts include: the PLPs (already discussed in Chapter 2), constellation rotation and scattered pilot patterns etc. These new concepts have their repercussions at both the framing structures and the signaling at any layer. In this chapter we primarily focus on the framing structures and the signaling fields affected by the novel concept of PLPs. Overall the chapter comprises a study about the logical and physical aspects of the framing structure and the physical layer signaling. Additionally, we investigate about the identification of a logical unit packet in a given DVB-T2 data flow.

In section 4.1 the logical framing structure is presented along with some details about the logical operations over a PLP prior to its mapping in the physical frames. Section 4.2 explains the composition of the physical frames carrying a DVB-T2 transmission and some details about the PLP mapping. Section 4.3 is devoted to the physical signaling, which is the most important part of each unit frame of a DVB-T2 transmission. At the end in section 4.4 we summarize our study, underline the relevance of this study and relate our findings with the theme of the thesis work.

4.1 Logical Frame Structure

The unit packets of a PLP go through a chain of operations prior to their mapping in the physical framing structures. Those operations include: FEC coding, constellation mapping, time interleaving and scheduling. Conceptually, the logical framing structure in a DVB-T2 system is PLP-oriented. Indeed the parametric values for the operations like FEC coding, constellation mapping and interleaving are chosen as per the requirements of the robustness and the throughput properties of a given PLP. The

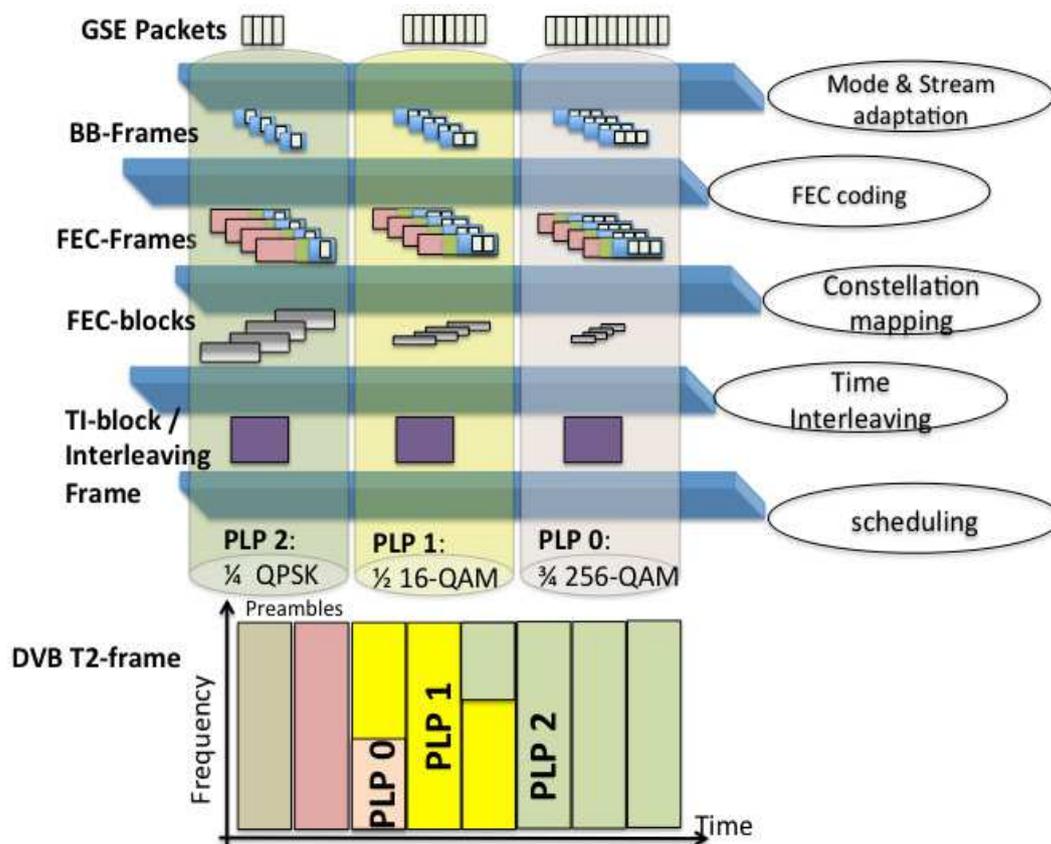


Figure 4.1: DVB-T2 Transmission chain

building blocks of a DVB-T2 logical framing structure include: Base Band (BB) frames, FEC Frames, FEC blocks, Time Interleaving (TI)-blocks and Interleaving frames. In Figure 4.1 all the logical stages of DVB-T2 data flow are shown till the mapping of PLPs in a DVB-T2 frame, which is the unit frame of the physical framing structure. (refer section 4.2)

4.1.1 GS/TS Streams

A DVB-T2 system serves as a transport mechanism, which maintains an independence with respect to the choice of the stream transported. A DVB-T2 data packet may carry several packets of a GS [56, 57] (or a part of the MPEG TS). The header portion of each of the DVB-T2 unit packet contains the information regarding a successful recovery of the GS/TS streams at the DVB receiver side.

4.1.2 Baseband Frames (BB-frame)

A BB-frame is the fundamental data unit of the logical framing structure of a DVB-T2 system. A DVB-T2 system allocates radio resources and schedules the input TS/GS streams in the whole number of BB-frames.

The input to a DVB T2-system may consist of several logical data streams. Each logical data stream is carried by one data PLP. Indeed a PLP is a transport structure through a DVB T2-system with some predefined parameter values. The BB-frames are the basic units on that transport structure. Each BB-frame is specific to a given PLP.

BB-frame header

A BB-frame contains a BB-header, which carries the information about the start of the first GS packet (or the position of the start of a TS stream part in the data field) and the length of the data field. A BB-header has a fixed length of 10 bytes.

Some of the important fields of a BB-header are: User packet length (UPL), data field length (DFL), number of bits (i.e. bit distance) between the User Packet and the start of Data field of the BB-Frame (SYNCD)¹, CRC-8 bits to detect errors in the BB Header.

There are also two bytes (i.e. MATYPE) carrying bit flags which provide information regarding the payload format, constant or variable modulation coding, stream synchronization, choice between a single and a multiple stream transmission and the PLP identity (also called Input stream Identifier).

BB-frame 's organisation

A logical data stream passes through two processes to produce the BB-frames for a PLP carrying the GS/TS. Those processes are:

1. Mode adaptation
2. Stream adaptation

The mode adaptation operates separately on each PLP carrying a data flow or a TS/GS stream. The considered TS/GS stream is sliced into data fields. The mode adaptation module processes the input data and selects one of the two modes, normal

¹e.g. SYNCD = 0 means a complete alignment, for SYNCD = 65535D, means there is no start of any user packet in the Data field

mode or high efficiency mode for the packetization of the given TS/GS stream. Each mode has mode specific repercussions on the composition of the BB-header

An illustration of the structure of BB-frame in normal mode can be found in Figure 4.2.

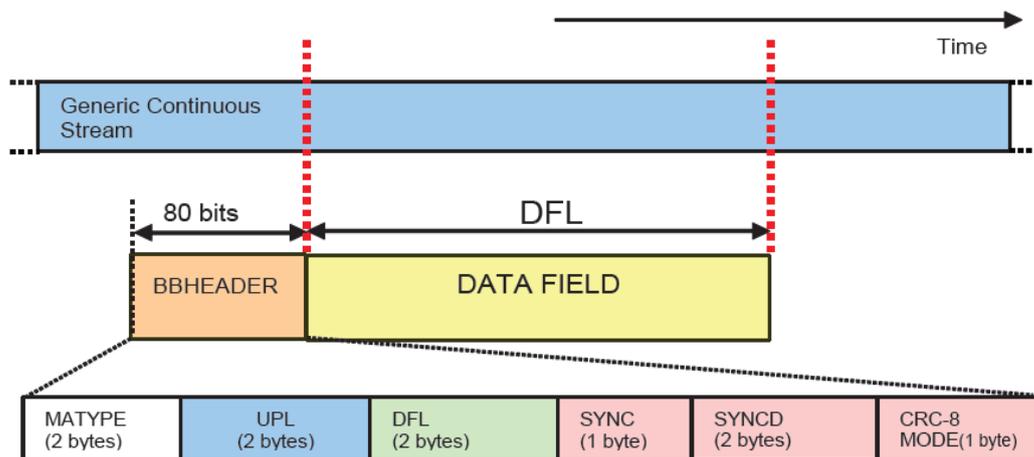


Figure 4.2: BB-frame structure for Normal Mode[1]

The mode adaptation of a GS/TS is followed by the stream adaptation procedure to complete the formation of the BB-frames. The stream adaptation comprises of three steps, including:

- Scheduling: This includes decisions regarding mapping of PLPs on the physical OFDM signal.
- Padding: The construction of a BB-frame is followed by FEC coding for a given FEC code rate and a fixed FEC codeword length. The padding fields are added to the BB-frame in the case when the available BB-frame data is not sufficient to fill the data field. These fields are used for the in-band signaling, which contains the L1-signaling and signaling for the higher layers.
- Scrambling: The entire BB-frame is randomized through a known Pseudo Random Binary Sequence.

4.1.3 FEC Frame

The FEC coding chain for a DVB-T2 signal comprises:

- BCH code

Table 4.1: FEC Coding parametric values

FEC frame length, n_{LDPC} bits	LDPC code rate (effective)	BCH codeword length, n_{BCH} bits	BCH parity bits, $n_{BCH} - k_{BCH}$ bits	BB-frame length, k_{BCH} bits
16200	1/4 (1/5)	3240	168	3072
16200	1/2 (4/9)	7200	168	7032
16200	5/6 (37/45)	13320	168	13152

- LDPC code

A BB-frame is treated as an information word length k_{BCH} , by the BCH encoder, which adds some parity bits to the BB-frame and gives a BCH codeword length, n_{BCH} . The codeword from a BCH encoder serves as an information word for the LDPC encoder. The codeword obtained from a LDPC encoder is called a FEC frame. There are two possible lengths of an FEC frame, n_{LDPC} :

1. Normal FEC frame, 64800 bits long
2. Short FEC frame, 16200 bits long

For a T2-lite profile transmission only short FEC frames are used [26]. In Table 4.1, we present some of the possible BB-frame sizes for a short FEC frame. For a short FEC frame the BCH encoder appends 168 parity bits, which can correct up to 12 bits in error. The number of parity bits from a BCH code is small compared to the size of the BB-frame. Therefore, the code rate for a FEC coding chain is pre-dominantly determined by the LDPC coding. It can be noticed in Table 4.1 that for the short FEC frames the exact standard code rates are not achievable which is due to the limitations of the LDPC parity bits grouping [26].

In Figure 4.3 we illustrate a FEC frame, comprising a BB-frame with the parity bits from both of the constituent encoders of the FEC coding chain.

4.1.4 FEC-Blocks

The FEC-frames are bit-interleaved and arranged into words, which are then mapped onto constellation points and then to the OFDM cells. An OFDM cell is the physical resource unit of a DVB-T2 OFDM signal, which is explained in Section 4.2.2. The bit-interleaver used is called column-twist interleaver. The set of constellation points

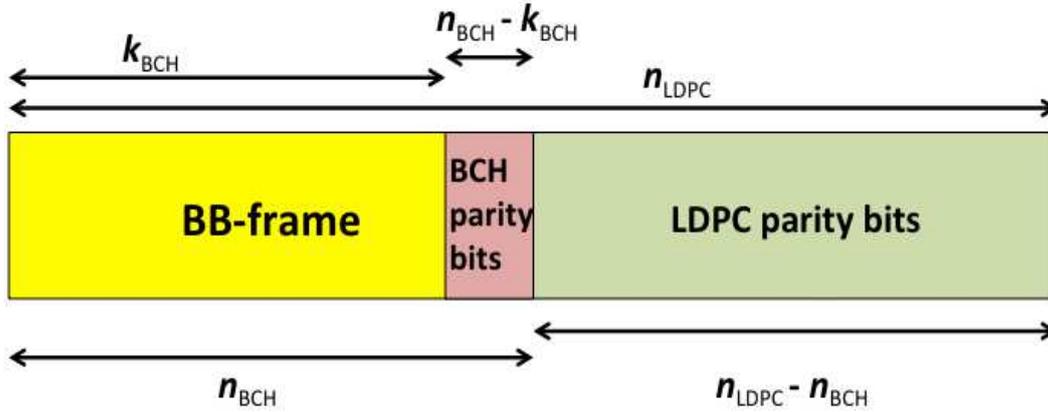


Figure 4.3: BB Frame Formation for Normal Mode

corresponding to one FEC frame is known as a FEC block. The number of cells for a FEC-block depends on both the order of the modulation used for the constellation points and the size of the FEC frame for a particular PLP.

For example, a short FEC frame spans over 8100 OFDM cells for a QPSK modulated constellation but it includes 2025 OFDM cells per FEC-block for a 256-QAM modulated constellation, Table 11 [26]. All FEC-blocks go through a cell interleaver which interleaves OFDM cells for each FEC-block. Before, cell interleaving it may also go through constellation rotation if required.

4.1.5 Interleaving Frame

An Interleaving Frame is the unit framing structure in which the scheduler performs the mapping for a particular PLP in the physical framing structure. An interleaving frame may comprise one or several physical unit frames i.e. T2-frames.

In an interleaving frame the PLP appears in one T2-frame in every I_{JUMP} T2-frames. A T2-frame is an OFDM frame, which is the basic unit of the DVB-T2 physical framing structure (refer to Section 4.2.1). If an interleaving frame comprises P_I T2-frames then the total duration of an Interleaving Frame is P_I T2-frames (the T2-frames in which the PLP is mapped) plus the $P_I(I_{JUMP} - 1)$ T2 frames which are skipped, which becomes $P_I I_{JUMP}$ T2-frames.

The example in Figure 4.4 shows the mapping of a PLP in every 3rd T2-frame, whereas the considered PLP has each interleaving frame comprising three T2-frames. Thus each Interleaving frame duration is equal to 9 T2-frames.

In the logical dimension a scheduler configures a whole number of FEC-blocks to each Interleaving Frame, which is dynamically variable. The FEC-blocks in an inter-

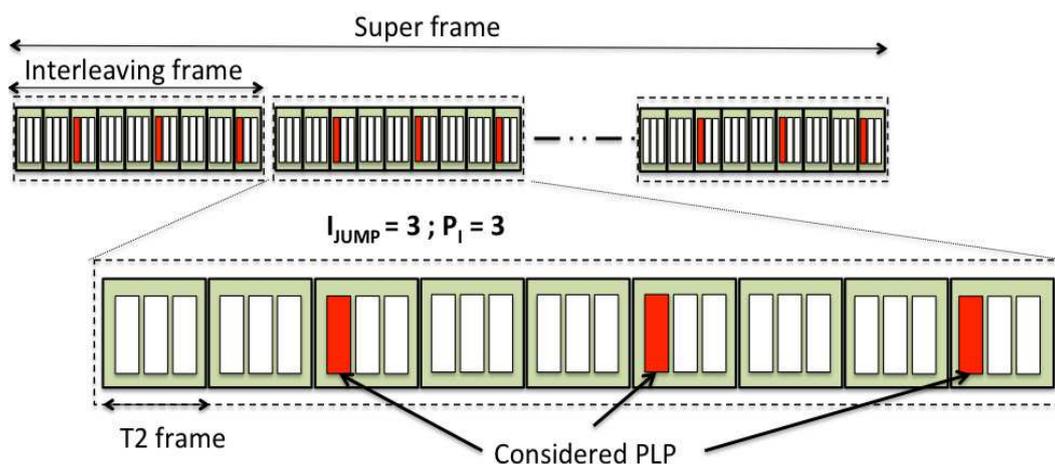


Figure 4.4: Interleaving frame

leaving frame are also time interleaved and grouped in sub-blocks called Time Interleaving (TI)-blocks. (refer section 4.1.6)

4.1.6 Time Interleaving (TI)-block

A sequence of FEC blocks from a particular PLP belongs to the same Time Interleaving (TI)-block, if their OFDM cells are time interleaved together by the time interleaver in a given memory space. The detailed procedure of time interleaving is explained in section 6 of [26]. A TI-block structure is also specific to a PLP, as the depth of time interleaving is one of the parameters affecting the robustness of a PLP.

There can be one or several TI-blocks grouped in an Interleaving frame. The L1-signaling contains information about the use of time interleaving, number of TI-blocks per interleaving frame and also the number of maximum FEC-blocks per interleaving frame.

There are three standardized cases regarding the number of TI-blocks per interleaving frame and their mapping in T2-frames (see Figure 4.5 also):

1. Several TI-blocks per interleaving frame and each interleaving frame is mapped over one T2-frame.
2. One TI-block per interleaving frame and each interleaving frame is mapped over one T2-frame.
3. One TI-block per interleaving frame and each interleaving frame is mapped over several T2-frames.

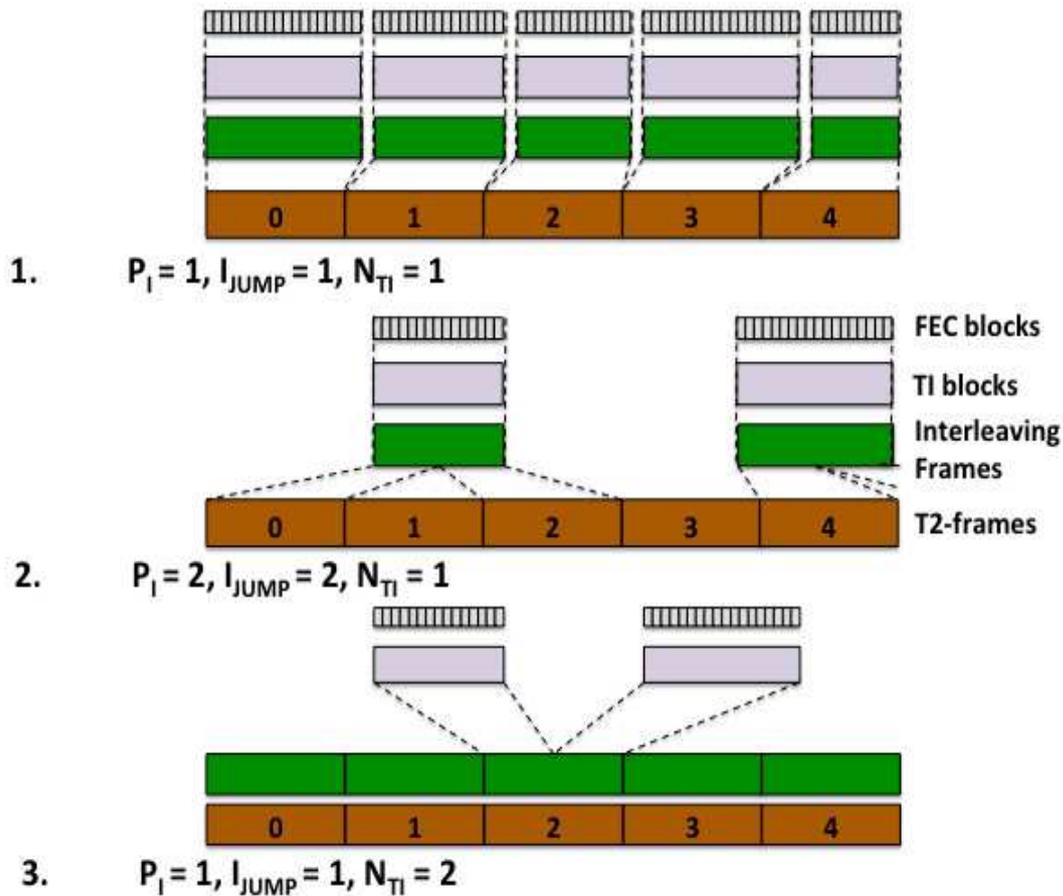


Figure 4.5: The three standardized cases of Time interleaving

The use of multiple TI blocks per interleaving frame is preferable for the high throughput PLPs for a given T2-frame size.

4.2 Physical Frame Structure

The Physical framing structure is fundamentally based on the OFDM frames, called T2-frames and the bigger frames called superframes which comprise several T2-frames and sometimes some non DVB-T2-frames. The non-DVB-T2-frames are basically included for the futuristic pro-handheld DVB profiles. Such frames are called the Future Extension Frames (FEFs). The physical framing structure is related to the logical framing via PLPs. Thus we also include a brief presentation of the concept of PLP mapping over a DVB-T2 frame.

4.2.1 T2-Frame

A T2-Frame is a sequence of OFDM symbols. It comprises: one P1-symbol, a configurable number of both P2-symbols and data symbols. The P1-symbol and the N_{P2} P2-symbols are also collectively called the signaling preambles.

The duration of a T2-Frame is determined by the FFT size, guard interval and the number of symbols used. The maximum allowed T2-frame length is 250 ms, which imposes a limit on the maximum number of OFDM symbols L_F for a given FFT size and guard interval. The values for N_{P2} are fixed for a given choice of the FFT size, Table 45 of [26]. The T2-frame time length can be expressed as,

$$T_F = L_F T_s + T_{P1}, \quad (4.1)$$

where, T_s is the total OFDM symbol duration, L_F is the total number of the OFDM symbols including the N_{P2} P2-symbols also and T_{P1} is the P1-symbol duration which is always 224 μ s. There can be 60 to 2098 symbols in each T2-Frame for a 8 MHz bandwidth system, depending on the choice of the allowed FFT sizes and GIFs, Table 8 of [3]. In Figure 4.6 we illustrate the DVB-T2 physical framing structure.

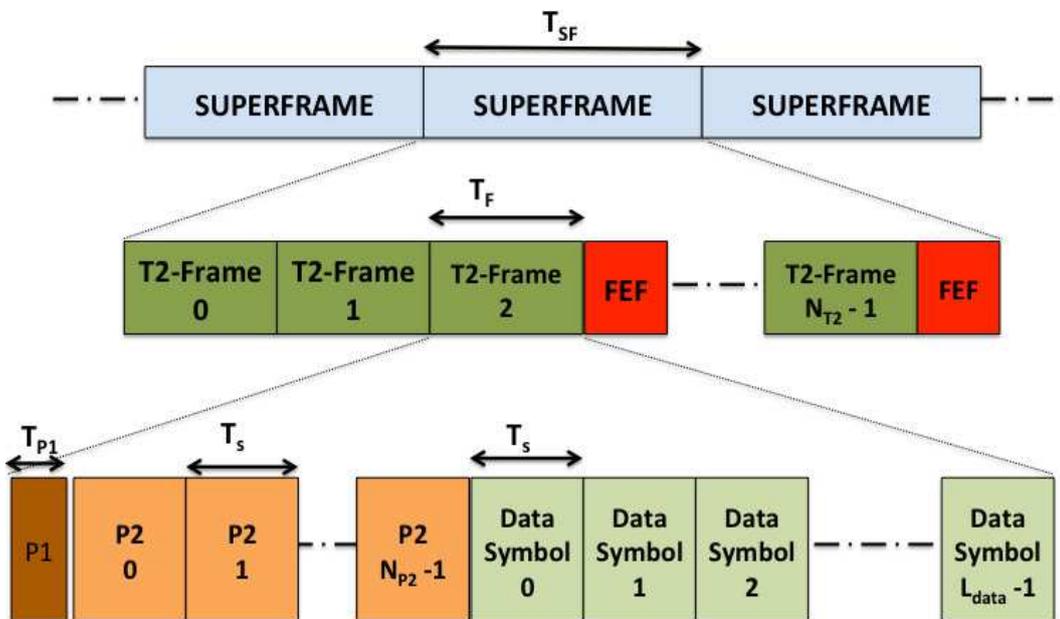


Figure 4.6: DVB T2 Physical Framing structure[3]

4.2.2 OFDM cells

An OFDM cell is the bandwidth associated to a subcarrier in one OFDM symbol, and can be modulated by one constellation point, pilot or reserved tone [1]. In the Long Term Evolution (LTE) vocabulary an OFDM cell is called a Resource Element.

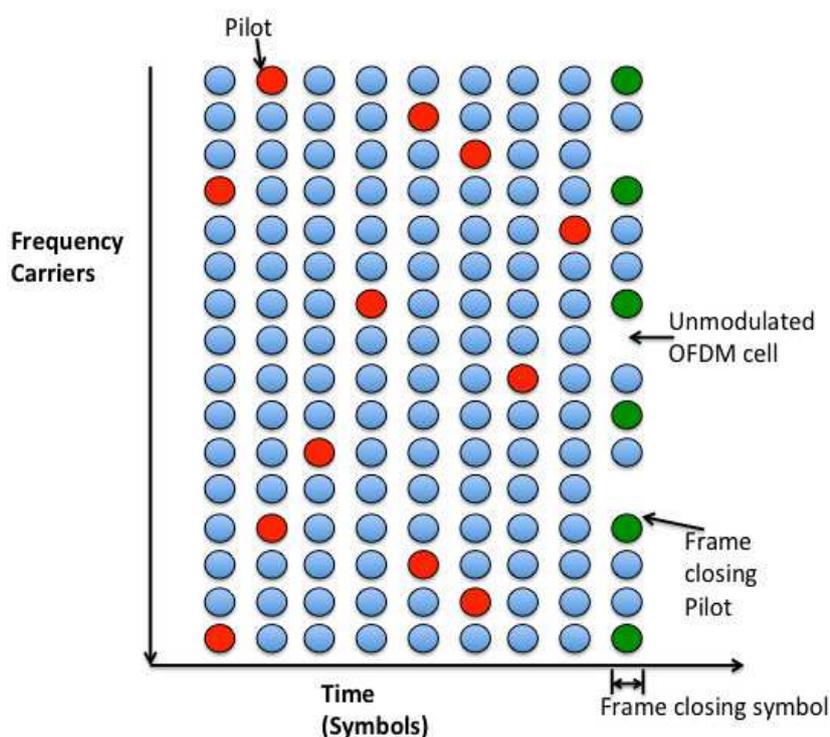


Figure 4.7: Pilot and active OFDM cells in Normal and Frame closing symbols[3]

Sometimes a T2-frame ends with a special OFDM symbol called frame-closing symbol. A frame closing symbol has a higher pilot density. Therefore some OFDM cells are left unmodulated (set to zero) to ensure that the frame-closing symbol has the same power as other symbols. (see Figure 4.7)

4.2.3 Mapping of PLPs into the T2-Frames

The mapping of PLPs over a T2-frame follows a certain standardized order. A PLP is either a data PLP or a common PLP (refer to Chapter 2). The mentioned data PLPs are further classified into two types. Namely,

1. Type 1 data PLP
2. Type 2 data PLP

The two types of data PLPs are different on the basis of the number of sub-slices per T2-frame. A sub-slice is defined as a group of active OFDM cells from a single PLP which are transmitted on successive cell addresses over a single RF channel. At the end of this section we explain some details about the cell-addressing and present them in Figure 4.9.

A Type 1 data PLP is carried by just one sub-slice in a T2 frame. Whereas, a Type 2 data PLP is carried in multiple sub-slices per T2-frame. The number of sub-slices per T2-frame is the same for all type 2 data PLPs (within a superframe), which can range from 2 to 6480 sub-slices. In a T2-frame all sub-slices of a particular PLP are equal in length and each of the two successive sub-slices of the same PLP are separated by the same number of OFDM cells called sub-slice interval.

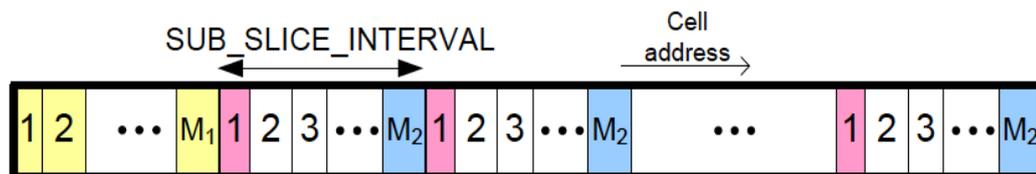


Figure 4.8: Mapping order of the Data PLP Subslices along the increasing cell index in a T2 frame [3]

In Figure 4.8, there are M_1 data PLPs of type 1 and M_2 data PLPs of type 2. It can be noticed that all type 1 data PLPs are scheduled to occur before type 2. Moreover, there are more than one sub-slices for each of the M_2 data PLPs of type 2.

The PLPs of type 1 offer better power saving, because of having one sub-slice per T2-frame. This enables a receiver to switch-on only for the relevant sub-slice and then it can be switched-off for the rest of the T2-frame. In the case of the type 2 PLPs a receiver either remains switched on throughout or it switches-on/off during each T2-frame, which is less power efficient. However, the type 2 PLPs are more robust against any temporal fading phenomena because of the better time diversity [58].

A P1-symbol is the first preamble and the most robust part of a T2-frame. It carries several signaling bits with a high detection probability. Those bits convey some basic parametric values of the OFDM signal (i.e. for a given superframe). The P2 symbols carry the entire physical signaling which includes the retransmission of the signaling bits from the P1-symbol as well. There are two parts of the physical or Layer 1 (L1)-signaling carried by the P2-symbols, namely, L1-presignaling and L1-postsignaling. We devote section 4.3 to explain the details about the L1-signaling and the information carried in some important fields. There is a fixed number of P2-symbols for a given FFT size of the OFDM signal, which may leave some of the OFDM cells unused in the

P2-symbols. In principle only the data symbols can carry the PLPs but the DVB-T2 standard allows the usage of those unused cells for the mapping of the PLPs.

The mapping of the L1-signaling, PLPs and auxiliary streams into the OFDM symbols of the T2-frame is depicted in Figure 4.9. The mapping order can be understood as P1-signaling, L1-signaling, Common PLPs, Data PLPs Type 1, Data PLPs Type 2, auxiliary streams and the dummy cells (refer to section 4.2.7).

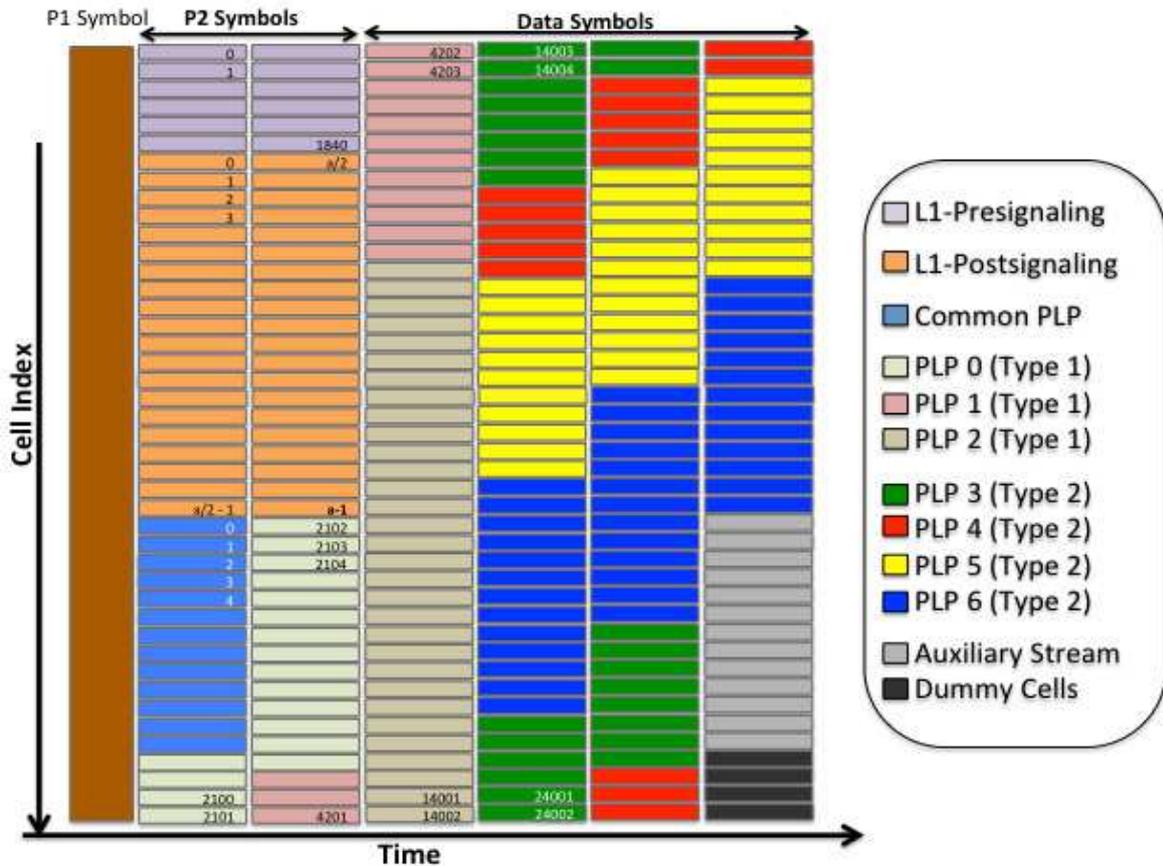


Figure 4.9: T2-frame mapping with different types of PLPs

Cell-addressing

In a T2-frame the OFDM cells for L1-signaling and for PLPs are addressed separately. The OFDM cells used by the two parts of the L1-signaling are also indexed separately. Both parts of the L1-signaling are evenly distributed among all the N_{P2} P2-symbols², such that there is an equal number of OFDM cells per P2-symbol which is used for carrying either of the two parts of the L1-signaling.

²The value of N_{P2} is fixed for each FFT size of the OFDM signal [26]

As we already mentioned that standards permit mapping PLPs to the unused OFDM cells of the P2-symbols. Thus the first available cell after the L1-signaling in the first P2 symbol has the cell address '0'. The cell address increases up to the end of the P2 symbol and then continues from the first available cell in the next P2 symbol.³ In Figure 4.9, we present the concept of cell-indexing along with mapping of PLPs in a T2-frame.

4.2.4 P1-Symbol

A P1-symbol serves as the first preamble for each T2 frame. A P1-symbol enables: detection of the DVB signal and a quick scan of system parameters, [3].

The P1-symbol is Differential-BPSK modulated. The FFT size is 1k for the OFDM modulation of this symbol. A P1-symbol has two additional portions comprising the cyclic repetition of the modified version of the P1-symbol. The total time length of the symbol 224 μ s long for a 8 MHz system.

4.2.5 Superframe

In the physical framing structure the biggest transmission unit is called a superframe. A superframe is just a group of OFDM frames, which always comprises several T2-frames. The length of a superframe can vary from 2 to 255 T2-frames. Additionally, it may also contain 255 or lesser number of the OFDM frames carrying a non-DVB-T2 profile, such frames are called Future Extension Frames (FEFs) as shown in Figure 4.6. A FEF can be as long as 250 ms at maximum. The time duration for a T2-frame and a FEF belonging to the same superframe doesnot need to be same. However, within a superframe, all T2-frames should have equal time length, similarly all FEFs should also have the same time length.

The maximum length of a super frame is 63.75 s (i.e. 255 x 250 ms = 63.75), without FEFs, which extends to 127.5 s (i.e. 255 x 2 x 250 ms = 127.5) with FEFs. Typically, there are two T2-frames per superframe without FEFs [59].

4.2.6 Future Extension Frames

The purpose of the FEFs is to enable flexible mixing of the services to be defined in a future version of the standard with the services defined in the current DVB-T2

³The cell address includes only the cells available for data transmission, not the pilot or tone reservation cells.

standard. The examples of the possible FEF application include: the recently proposed T2-lite or T2-mobile profile [18, 26, 60] and the DVB-Next Generation Handheld (DVB-NGH)-profile [15].

A FEF also has a P1-symbol which enables a conventional DVB receiver to detect the presence of a new-profile. At the same time it helps a new-profile-enabled receiver to read and decode the relevant FEFs only.

4.2.7 Dummy cells and Auxiliary Streams

The DVB cells left unused due to the unavailability of the data are called 'Dummy Cells', which are modulated with some opportunistic data flows, called 'Auxiliary streams'. Some of the examples of the auxiliary streams include: DVB transmitters identification, low data audio streams and monitoring DVB receivers via relay transmitters etc [3].

4.3 Layer 1 (L1)-Signaling

The L1-signaling consists of three sections, which can be listed in the mapping order in a T2-frame as:

1. P1-signaling
2. L1- presignaling
3. L1- postsignaling

Each section includes a more detailed level of signaling information and the information required to receive the following part. A successful reception of the mentioned chain of signaling stages is incumbent for the reception of the PLPs mapped to the data symbols of each T2-frame. In Figure 4.10 an illustration underlines the position of L1-signaling and its components in a T2-frame structure.

4.3.1 P1-Signaling

The seven bits carried by a P1-symbol are also called P1-signaling (see Figure 4.10). These bits act as a prelude of the entire L1-signaling. These bits carry information about: the format of the T2-frame regarding use of the Multiple Input Single Output (MISO) and the T2-lite profile (i.e. S1), the FFT size used for the OFDM signal

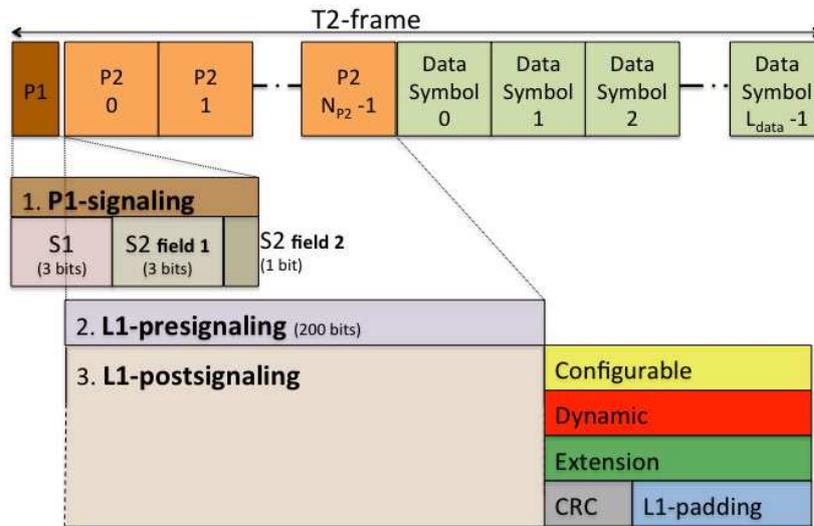


Figure 4.10: L1 Signaling structure

generation (i.e. S2 field 1) and the inclusion of the FEFs in the superframe (i.e. S2 field 2).

4.3.2 L1-presignaling

L1-presignaling is transmitted using the P2-symbols along with the L1-postsignaling. The L1-presignaling consists of 200 bits, which are coded at 1/5 effective LDPC code rate. These coded bits are modulated using Binary Phase Shift Keying (BPSK) constellation.

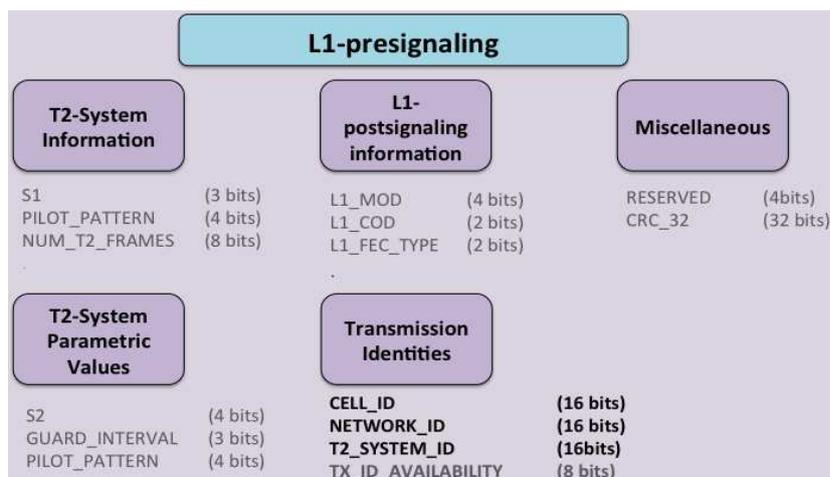


Figure 4.11: L1-presignaling fields categorized as per their utility

The values for the L1-presignaling fields are fixed for all the T2-frames of the superframe. The information carried in those fields is about: the T2-system parameters, the

identities of several entities in a DVB-T2 network and some parametric values for the DVB transmission. We classify the information into five different categories as follows (also see Figure 4.11):

1. **Transmission Identities:** There are three 16 bits fields carrying the identification data about the origin of a DVB-T2 transmission:
 - **NETWORK_ID:** It carries the DVB network ID which is unique within a geographical region defined by a Country Code (e.g. 250 for France and 840 for US) ⁴[61, 62].
 - **T2_SYS_ID:** It identifies a T2-system. (see the definition of a T2-system in section 2.2.1)
 - **CELL_ID:** It carries the identity of the DVB cell (see [63]) from where a given stream originates. It is mainly used to differentiate the PLPs carrying some local transmission.
2. **T2-system Information:** These are the L1-presignaling fields which include: information about physical framing structure, S1-field from P1-signaling, information about the type of input formats e.g. TS, GS etc and information about the Time Frequency Slicing (TFS) [3, 64].
3. **T2-system parametric values:** These fields directly point to the standardized values for parameters like FFT size used for OFDM signal, guard interval and pilot patterns.
4. **L1-postsignaling information:** In this category all fields carry information about the parametric choices and the structure of L1-postsignaling. For instance, modulation scheme and FEC code rate.
5. **Miscellaneous :** There are 4 bits reserved for future use and are currently usable for some physical layer procedures to remove the bias in the signal [26]. Besides, the entire L1-presignalling is protected by a 32 bit Cyclic Redundancy Check (CRC) error detection code. Those 32 parity bits are also a part of the L1-presignaling.

4.3.3 L1-postsignaling

The L1-postsignaling is carried in the P2-symbols following the L1-presignaling (see in Figure 4.9). The modulation scheme and code rate for the L1-postsignaling data is

⁴Country codes are used for the satellite based multi-country DVB networks, the terrestrial networks are single country networks.

signaled in the L1-presignaling. Normally, a more robust modulation scheme and code rate is selected for the L1-postsignaling w.r.t. the data PLPs.

The L1-postsignaling contains the values of the parameters for each PLP in the respective T2-frame. Thus an error free reception of the L1-postsignaling is a precondition for a successful data extraction of the PLPs.

Functionally there are two fixed components of the L1-postsignaling:

1. Configurable L1-postsignaling

The configurable part of the L1-postsignaling remains unchanged for all T2-frames in the superframe. The fields with the PLP-specific information are the most important sections in the configurable part of L1-postsignaling. We specifically focus on the fields carrying information about the logical organization of a PLP, because of their importance in the identification of the BB-frames.

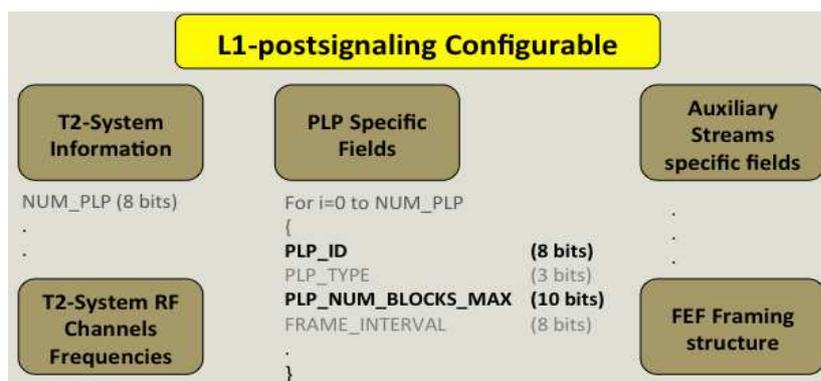


Figure 4.12: Important fields from the L1-postsignaling Configurable part

There are two important PLP-specific fields (also see Figure 4.12):

- **PLP_ID**: It is an 8 bit field, it uniquely identifies a PLP within a T2-system [1].
- **PLP_NUM_BLOCKS_MAX**: This is a 10 bit field which gives the configured maximum number of FEC blocks per interleaving frame.

The rest of the PLP specific fields include information about the time interleaving, constellation mapping and FEC coding of the given PLP.

Apart from the PLP specific information there are fields carrying general information about the total number of PLPs, T2-frame composition and FEF framing structure etc.

2. Dynamic L1-postsignaling

The dynamic part of the L1-postsignaling may change for each T2-frame of the super-frame. There are two fields important for the unique identification of a BB-frame (see Figure 4.13):

- **FRAME_IDX**: it is a 8 bit field which manages the count of the T2-frames for their indexing within the superframe.
- **PLP_NUM_BLOCKS**: It is a 10 bit field which gives the exact number of FEC blocks per interleaving frame.

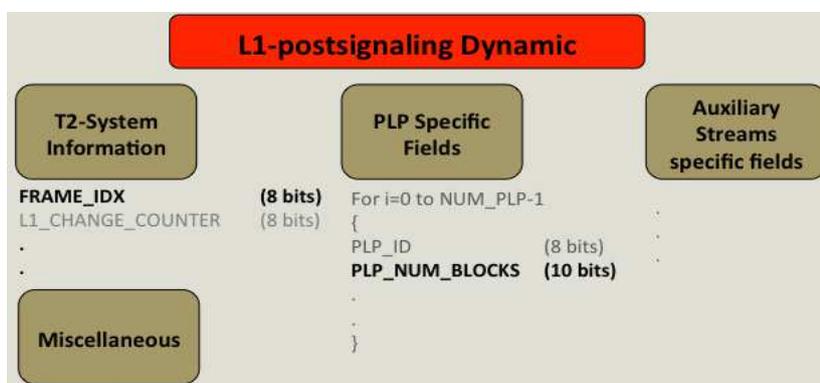


Figure 4.13: L1-postsignalling Dynamic part

Maximum number of PLPs

The number of the OFDM cells occupied by the L1-postsignaling depends on the number of signaling bits and the constellation used for L1-postsignaling data. The L1-postsignaling can be modulated using BPSK, QPSK, 16-QAM or 64-QAM⁵. The number of signaling bits in L1-postsignaling is related to the number of PLPs, number of auxiliary streams, the use of FEFs and the possible future use of TFS.

Thus, the number of PLPs which can be carried by the T2-system is limited by the modulation used for L1-postsignaling and the number of signaling bits. The maximum number of PLPs can be from 14 to 255 for different FFT sizes and modulation schemes used. It is observed that the number of PLPs carried in a superframe increases for a higher order of constellation mapping and a larger FFT size for the OFDM modulation, see Table 45 of [26].

⁵The FEC code rate is always 1/2.

4.4 Summary

The video encoded data flows are multiplexed to form a GS/TS stream. Each data flow (i.e. an MPEG data flow or GS encapsulated packets flow) is transported via a data PLP. The data flow elements (part of MPEG flow or GSE packets) are scheduled in the BB-frames of the relevant data PLP. The BB-frames of each PLP are FEC coded, mapped to constellation points and time interleaved to form FEC frames, FEC blocks and TI-blocks respectively.

The parameter values for each of the operation on the BB-frames depend on the robustness and throughput properties of the respective PLP. The TI-blocks of the PLP are mapped in the OFDM frames called T2-frames. Each PLP is scheduled in the T2-frames based on the structure of its interleaving frame. Each interleaving frame may comprise one or several T2-frames. A T2-frame includes: the physical layer signaling called L1-signaling and the data PLPs. The L1-signaling is carried in special OFDM symbols, namely P1 and P2 symbols. The P1 and P2 symbols are robust and have a high detection probability.

Some of the fields from the L1-signaling data, which are important for the identification of a BB-frame from a given PLP include:

- DVB Network ID
- DVB-T2 System ID
- DVB Cell ID
- PLP ID
- FRAME_IDX
- PLP_NUM_BLOCKS

The identification of a specific BB-frame in a DVB-T2 system is not straightforward because of the absence of an explicit BB-frame-indexing in a given PLP structure. In addition, the superframes are also not indexed. Since a T2-frame's index is unique only within a superframe, therefore two BB-frames mapped in the T2-frames from different superframes but having same T2-frame index value cannot be uniquely identified in a T2-system. The BB-frame identification in a DVB-T2 transmission is an important concept in the perspective of the thesis work.

The primary goal of this chapter was to point out these elements from a T2-framing structure, which are useful in the identification of a BB-frame in a T2-system. In

Chapter 6 and 5 we elaborate the idea of retransmitting the missing BB-frames in a DVB transmission, via an out-of-band transmission mechanism i.e. a cellular network. The proposed solution for the identification of the missing BB-frames is based on the findings of the current chapter.

Real-time Flow Repair Service based on LTE network

The concept of repairing a broadcasted file for each receiver individually via an out-of-band retransmission is already known [65]. In this chapter we propose the Real-time Flow Repair (RFR) service based on cellular networks for broadcast data-flows to the handheld receivers. In this regard we specifically consider a DVB-T2 broadcast transmission to the smartphones. The smartphones experience a double coverage i.e. from a DVB and an LTE networks. The proposed real-time repair is based on a recently specified client-server protocol i.e. Constrained Application Protocol (CoAP). Moreover, we envision a mutually co-ordinated infra-structure for the DVB-T2 System and the LTE core network. This co-ordination is realized by the RFR server, which is the only common entity to both infrastructures. An RFR server is considered on alternate locations, which also includes the localized positions of an RFR server using Selective IP Traffic Offload (SIPTO) and Local IP Access (LIPA) techniques.

In Section 5.2 we present the concept of a realtime repair over a broadcast data flow and define our proposal for a Real-time Flow Repair (RFR) service based on the cellular network. In Section 5.3 we introduce CoAP and present our argument about the use of a light application protocol for the data-flow repair. Section 5.4 presents a method for the identification of a DVB unit data packet (i.e. Base Band - frame (BB-frame)). Additionally, this section outlines the major steps of the RFR service procedures. In Section 5.5 we discuss about the impact of maximum Round Trip Time (RTT) latency in the LTE network over the RFR procedures.

In Section 5.6 we give an overview of some of the fundamental concepts related to the LTE network architecture and present an infrastructure integrating a DVB-T2 system with the LTE Evolved Packet Core (EPC). We consider various locations of

RFR server using Selected IP Traffic Offload (SIPTO) and Local IP Access (LIPA) techniques. In the end, Section 5.7 concludes about the modification in the repair scheme for multimedia data flow to the smartphones. We also conclude that considering today's cellular network i.e. LTE, our proposal of a realtime repair over multimedia broadcast is implementable.

5.1 Introduction

Watching television on a smartphone is a popular service. If the cellular network provides this service using unicast, it will have to transmit the same flow to each user individually, which is not efficient. Broadcast is a preferable choice for a mass distribution of some popular content to the users. The conventional Digital Video Broadcasting (DVB) networks are optimized to broadcast standard and high definition video transmissions to fixed users with roof antennae.

A smartphone can decode the DVB transmission by integrating a DVB receiver. Compared to a fixed receiver, a handheld receiver (i.e. a smartphone) has a weaker link budget because of the configurational disadvantage. As discussed in Chapter 3 this disadvantage is mainly due to the low antenna gain to receive the DVB signal. At first, due to the shorter antenna height, the antenna height gain is lesser [7] w.r.t. a roof-top mounted antenna for a fixed receiver. Secondly, in a smartphone the antenna is designed to receive signals on higher frequency bands i.e. Cellular network frequencies. A DVB signal at lower frequency bands is attenuated because of the negative antenna gain (see (6.4)).

A broadcast network is conventionally unidirectional. Thus a DVB transmitter is indifferent to the loss of elements at the reception side. The DVB signals are coded using Forward Error Correction (FEC). This adds some coding gain in the link budget and helps a lower error rate at a lower signal power level compared to the previous broadcast technologies. However, our analysis in [66, 2] and Chapter 3 reveals that significant improvement in the DVB handheld coverage is required.

The retransmission of the missing elements for a bad signal reception is a classical way to improve the reliability of a non-ideal reception. In a conventional broadcast we do not have a bidirectional link and therefore we do not have feedback signals to trigger a partial or complete retransmission. But in the case of a smartphone receiving the DVB transmission we always have a bidirectional link with the cellular network. Therefore, a cellular network can retransmit the lost elements from a DVB reception to each smartphone on-ground.

5.2 Service Proposal

5.2.1 Context

The method used for a massive distribution of files is called 'Filecasting' i.e. broadcasting a file. The IP networks use File Delivery over Unidirectional Transport (FLUTE) protocol for filecasting [67, 68]. FLUTE is based on the principle of splitting a file into uniquely identifiable elements. The file elements are FEC coded to have a reliable reception but the verification of a successful reception by a feedback signal is not possible. In [65] Hechenleitner proposes a file repair mechanism based on HTTP protocol for DVB-H or IP Data-Casting (IPDC). In this procedure each receiver of a broadcasted file undertakes a post-broadcast file repair process. For the elements not received, a GET request is sent to a file repair server via a cellular network or a Wireless Local Area Network (WLAN) connection.

In the literature another well-known scheme for a post-broadcast repair process is to recover locally the missing elements of a broadcast transmission from a remote transmitter. For example in [69, 70] a peer-to-peer repair approach is considered. In this approach a data broadcast to several local nodes is considered via cellular network. The local nodes are physically close and form an 802.11-based adhoc network to cooperatively repair the data reception for each other. There are two bottlenecks for such a repair operation. At first, all the missing elements from the broadcast reception at a given local node may not be sufficiently available from the other local nodes. Moreover, such a distributed repair operation can be slow for a time-constrained streaming application.

5.2.2 Real-time Flow Repair (RFR) Service definition

A repair operation is fundamentally based on the retransmission of the lost packets in the data reception. In the case of a data flow there are no predefined time boundaries regarding the end of the data transfer. The phenomenon of losing packets is thus an ongoing process. Therefore, the repair operation has to be running side by side with the data flow, contrary to a post-data-transfer repair which is made after the completion of a file reception. In our work we propose a cellular network based Realtime Flow Repair (RFR) service, which repairs a broadcast data flow to the handheld receivers in realtime.

The RFR service operates between a server and a client. We consider a smartphone to be the RFR client. To support an RFR service a smartphone requires an on-chip

DVB receiver, an RFR application and a buffer. The cellular network has a dedicated server, which is configured for the RFR service. We assume that the RFR server can provide any missing DVB packet, whenever an RFR client requests for it via cellular network. The RFR server may either have a direct wired link with the DVB network content generation unit or may have a DVB receiver with a roof antenna, which receives the DVB signals at Quasi Error Free (QEF) level. In Figure 5.1 we show a DVB flow received by the smartphone using a common antenna for the broadcast and cellular network signals. This kind of antenna is referred as the integrated antenna in [7].

A real-time repair of a broadcast data flow to the smartphones requires to surmount four challenges :

1. The availability of the radio resources in the cellular network.
2. The identification of the data units from the broadcast data flow in an RFR server i.e. cellular network.
3. A fast retransmission of the lost data units via cellular link, to reinsure a real-time repair.
4. The cellular network link peculiarly poses a long Round Trip Time (RTT) delay after a long period of inactivity. The prolonged RTT delay due to inactivity is in the order of 100 ms, which is otherwise around 10 times shorter.

In our proposal a repair operation is invoked each time the DVB receiver detects an erroneous packet in the DVB flow. The DVB flow is buffered before it is forwarded to the video application for play-out in a smartphone. The buffer is used to delay the play-out by an amount of time long enough to allow the smartphone to request a retransmission of the missing DVB packet and receive it. (see Figure 5.2)

RFR service is foreseen to help achieving a better quality of service for the DVB transmission to the handheld receivers. This may enable an operator to earn some customer loyalty and some additional income from an elite customer willing to pay additional fee for such a service.

5.3 Realtime Repair with Constrained Application Protocol (CoAP)

The HTTP protocol is based on the Transmission Control Protocol (TCP) connections. In a post-transfer filecast repair process at the end of the file reception all the missing

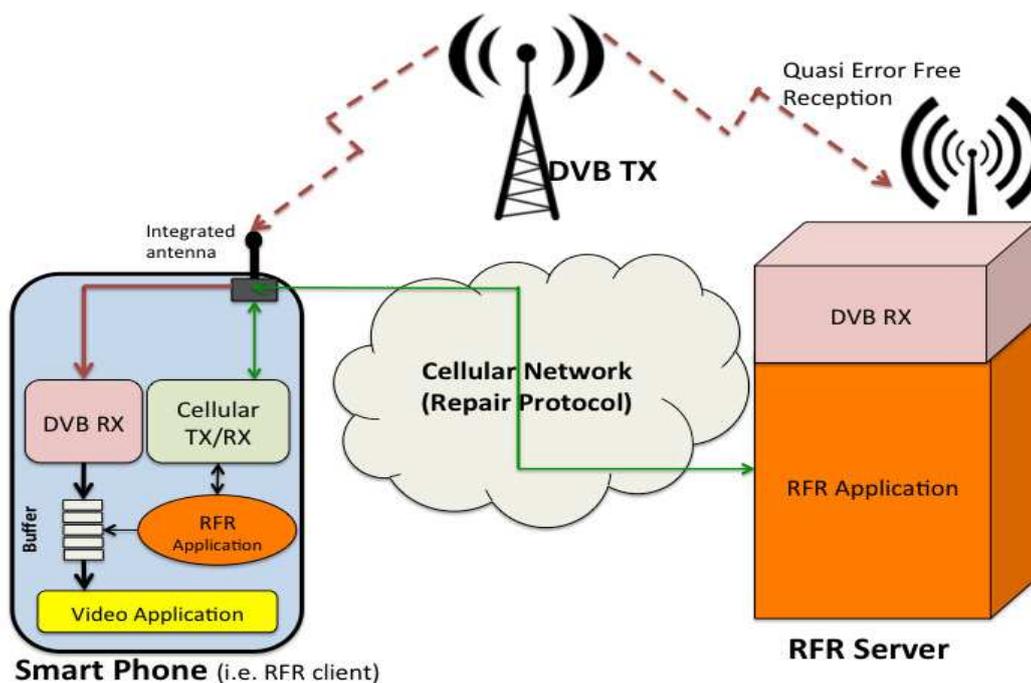


Figure 5.1: A simplified Architectural layout

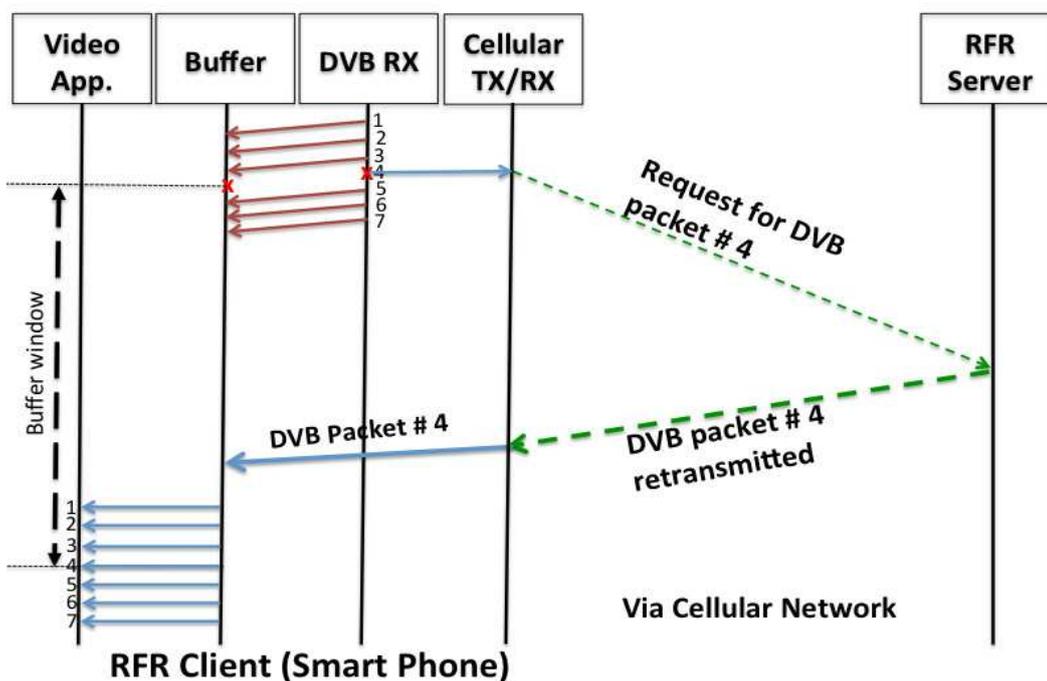


Figure 5.2: A simplified timing diagram of an RFR operation

elements are known. Thus, a file is repaired in a single TCP-session [65]. In comparison a broadcast DVB flow is not time bounded and the DVB packets may be lost on the fly. To repair a broadcast data flow a single TCP-session has to be maintained for all

the time the smartphone receives the DVB transmission. Another solution is to set up a new TCP-connection each time a DVB packet is lost.

In a cellular network link maintaining a long duration TCP-connection is expensive in terms of the signaling at the lower layers of the stack. According to [71] and [72], a TCP-connection responds to any data segment loss by triggering its congestion avoidance algorithms. A cellular network link can be lossy due to high BER and hand-offs [73]. The congestion avoidance algorithms may cause long communication pauses. Thus a TCP connection can potentially slow-down the proposed cellular network based repair service. Therefore, instead of HTTP, we use a User Datagram Protocol (UDP)-based application protocol, namely Constrained Application Protocol (CoAP).

5.3.1 Introduction to Constrained Application Protocol (CoAP)

Constrained Application Protocol (CoAP) is a client-server transfer protocol proposed to the Internet Engineering Task Force (IETF) for standardization. CoAP is applied to the nodes and networks with power and processing constraints [74, 75]. A considerable amount of work on CoAP has already been produced from industry and academia, which is in the form of building CoAP-based applications and exchange of the practical experiences.

CoAP is based on UDP, which makes it remarkably lighter than the TCP-based HTTP. The sensor networks is one of the most widely known example of CoAP applications.

CoAP supports some basic HTTP functions like GET and PUT and also supports some other functionalities like resource discovery and multicast [76, 77].

There are four types of CoAP messages:

- ◇ Confirmable message (CON): The sender of a CON message always waits for an acknowledgement from the receiver until a defined timeout. A sender retransmits a CON message if it does not receive an acknowledgement within the timeout period. The number of such retransmission attempts is also configurable.
- ◇ Non-confirmable message (NON): For NON messages a receiver does not need to acknowledge the reception of the message.
- ◇ Acknowledgement message (ACK): An ACK message carries the acknowledgement and the answer to the request if it is available. For example, if a CoAP-client sends

a request for a packet in a confirmable message, then the requested data packet will be attached to the ACK message by the CoAP-server.

- ◇ Reset message (RST): A RST message is used when the receiver is not able to read the received message.

In the header of a CoAP message there is a 16-bit field called 'Message ID (MID)' which uniquely identifies a confirmable and a non-confirmable message. The acknowledgement messages are related to their corresponding confirmable messages through MID. Similarly, the reset messages are also related to their corresponding Confirmable or Non confirmable messages through MID.

5.3.2 CoAP based RFR Service

A realtime repair of the data flow has to be fast. This is a constraint over time. The DVB flow consists of bursts of DVB packets. We perform a series of repair operations along with the DVB flow i.e. we request via cellular network for the retransmission of the lost packets.

CoAP is a protocol based on an asynchronous datagram transmission, which consumes lesser resources in comparison with HTTP. In order to add some reliability to the data transmission, the smartphone makes packet retransmission GET requests in the confirmable messages. For each request the RFR server sends the requested DVB packet in the acknowledgement message.

An illustration of the RFR service working for a simple implementation of CoAP can be seen in Figure 5.3.

5.4 Identification of the DVB unit data packet

5.4.1 BB-frame identification for the RFR service

When the receiver ends reading an interleaving frame, the DVB decoder obtains an ordered sequence of BB-frames. In Figure 5.4 the BB-frames are shown in an implicit sequence before FEC encoding at the transmitter side and after FEC decoding at the receiver side. The proposed repair operation tries to preserve the mentioned implicit sequence of the BB-frames in each interleaving frame. In our scheme we identify each BB-frame within an interleaving frame by its Implicit Sequence Number (ISN).

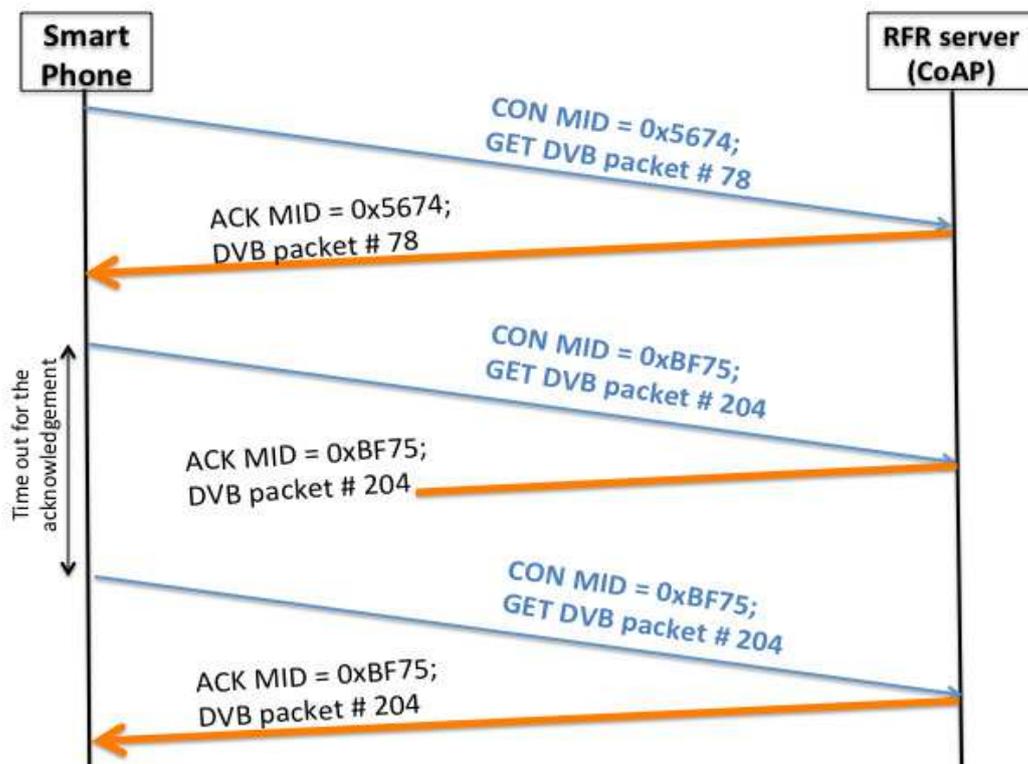


Figure 5.3: RFR service via LTE network for a simple implementation of CoAP

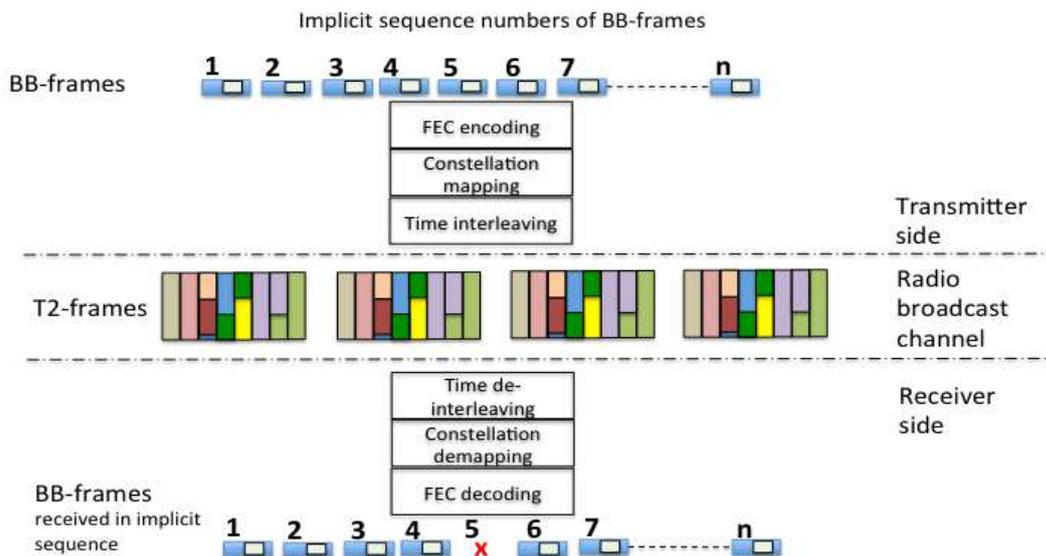


Figure 5.4: BB-frames Sequence order prior to the followed transformation

A BB-frame is associated to a unique PLP and for each PLP the indices of all the T2-frames carrying the PLP are known. We propose to identify each interleaving frame by the index value (FRAME_IDX) of the first T2-frame of the interleaving frame.

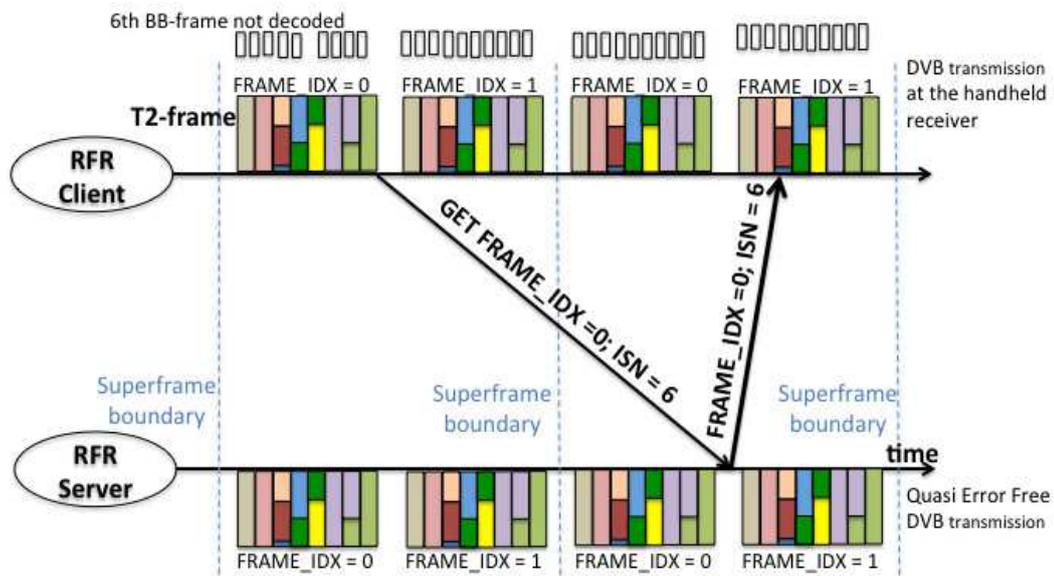


Figure 5.5: The LTE transmission delay and the BB-frame identification

The superframes of a DVB transmission do not have any index. As already mentioned, a typical cellular link poses an RTT delay in 100s of ms if used after a period of inactivity. Additionally, there is some probability of errors associated to a realistic cellular network link. Thus, a retransmitted BB-frame may arrive at the smartphone when it is receiving the BB-frames from the succeeding superframe. We illustrate this scenario in Figure 5.5.

In the buffer, two retransmitted BB-frames having same value of FRAME_IDX and ISN but belonging to two different superframes can be confused. Therefore we propose a superframe counter (SF_COUNT), for the unique identification of each retransmitted BB-frame in the buffer. The SF_COUNT is maintained by both ends (i.e. at the client side and at the server side). A synchronization procedure is also defined to ensure that both endsides have the same value of SF_COUNT for a given superframe (refer to section 5.4.2). Once synchronization is achieved then the SF_COUNT is incremented at both ends (i.e. SF_COUNT++) each time the FRAME_IDX field is reset.

Hence, to identify a BB-frame we first identify a PLP by using the following fields from the DVB-T2 signaling data (see Chapter 4):

- PLP_ID
- T2_SYS_ID
- NETWORK_ID
- CELL_ID

Table 5.1: RFR Exchanges: RFR Client to RFR Server

Message Type	Sent	Received
Subscription	NW_ID, T2_Sys_ID, Cell_ID	User_ID, Security token
Service Announcement	-	RFR server IP address, service schedule
Service Activation	User_ID, Security key	activation acknowledgement
Session start / close	PLP_ID	session start / close acknowledgement
GET Request	SF_COUNT / Frame_IDX / ISN	acknowledgment + BB-frame

Then to identify a BB-frame from an already identified PLP we propose the following to be used:

- Identification of the superframe using SF_COUNT
- Identification of the first T2-frame of the interleaving using FRAME_IDX
- Identification of a BB-frame within an interleaving frame using ISN

5.4.2 Specification of the RFR service procedures

We define an RFR service to comprise the following procedural steps: (see also Table 5.1)

Subscription

Subscription is the first step in starting a relationship between a service provider and a subscriber. A client passes his global location coordinates to get subscribed for the service. The service provider or operator determines the relevant NETWORK_ID, CELL_ID and T2_SYS_ID depending on the location coordinates of the user. The service provider saves this information in a database against a User ID. The User ID along with a security token is provided to the subscriber, which are used together in the service activation process.

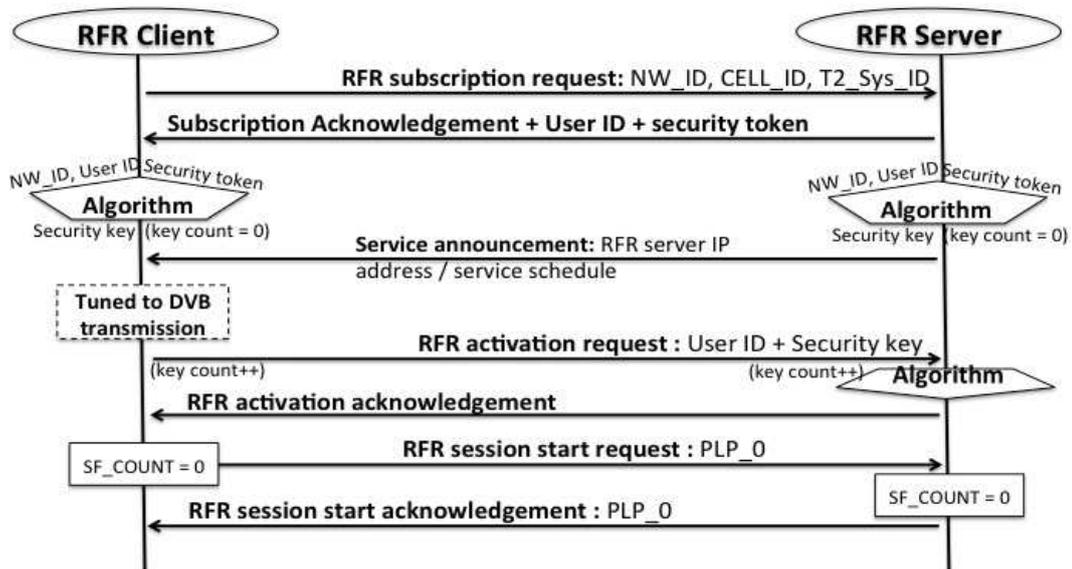


Figure 5.6: Major steps prior to repair operation

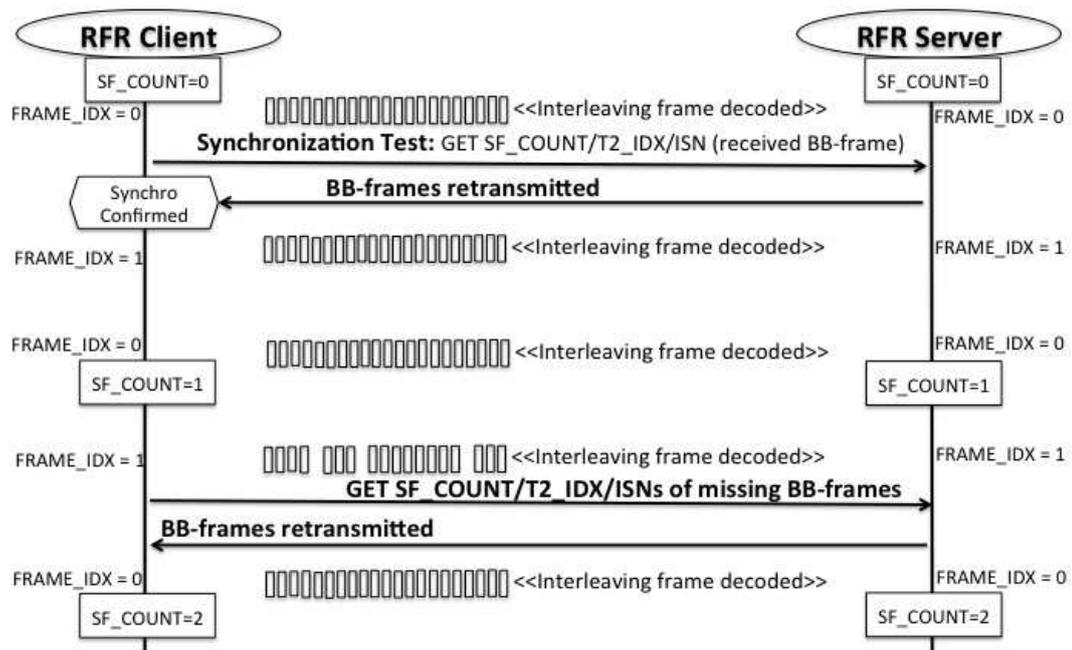


Figure 5.7: Repair operations along with the Broadcast data flow

Service Announcement

A service announcement contains details about the service access e.g. the IP address of the RFR Server and the availability schedule of the service etc. There can be several different ways to disseminate service announcements to both subscribers and non-subscribers. For instance, using Short Message Service (SMS) broadcast or web-based announcements on a Uniform Resource Locator (URL) which can be browsed.

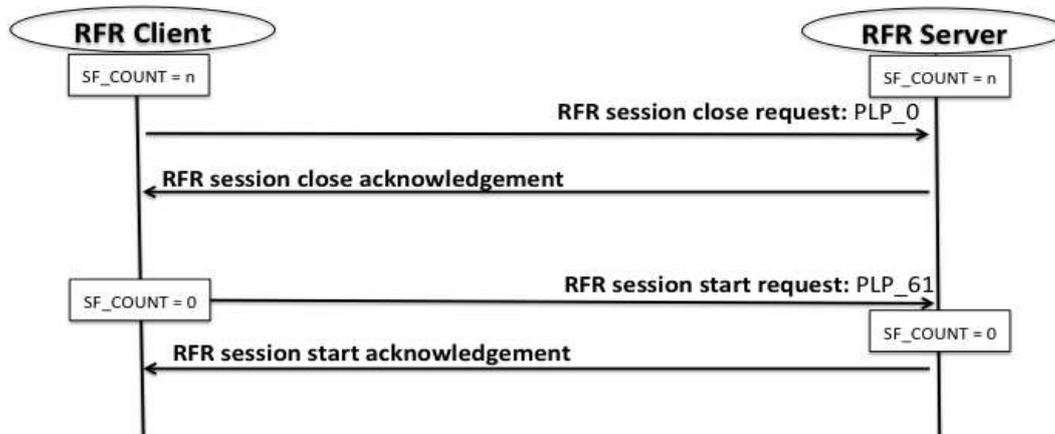


Figure 5.8: PLP switching

Service Activation

At the time when a smartphone starts receiving the DVB transmission, the RFR application in the smartphone sends a service activation request to the RFR server. The RFR application generates a security key by using the registered User ID and the security token provided at the time of subscription. A service activation request includes the User ID and the security key. The transferred security key is verified, to authenticate and approve the availability of the service for the user. After the verification, the RFR server sends an acknowledgement of the service activation.

RFR session

Once the smartphone receives an acknowledgement of the service activation, the RFR application triggers the smartphone to make a request for the start of an RFR Session. Each RFR session is specific to a particular PLP. Therefore, an RFR session-start-message is sent including the PLP ID of the PLP through which the smartphone is receiving data. The RFR server sends back an acknowledgement of the session start request, which confirms that the RFR server is ready to serve any request from the smartphone.

During an RFR session the RFR client and the server maintain the SF_COUNT. The SF_COUNT is reset at the start of an RFR session and is incremented every time the FRAME_IDX is reset during the session.

In an RFR session each time the DVB receiver completes decoding an interleaving frame, it acquires the implicit sequence numbers (ISNs) of all the BB-frames within the decoded interleaving frame. If one or more BB-frames are lost the RFR application

requests for their retransmission. As shown in Figure 5.7 the retransmission request includes the SF_COUNT value, the relevant FRAME_IDX and a list of the ISNs of the lost BB-frames i.e. SF_COUNT/ FRAME_IDX/ISNs.

SF_COUNT Synchronization test

As explained the SF_COUNT is maintained on both sides i.e. the client and the server. At the time of RFR session start request the SF_COUNT is reset by the client side. The RFR server resets the SF_COUNT only after receiving the RFR session start request. The RFR server and the RFR client are tuned to the realtime DVB transmission flow. The SF_COUNT field is incremented each time FRAME_IDX is reset. In the worst case scenario if the uplink transmission delay in the LTE network is longer than the T2-frame duration (i.e. typically 200 ms) then the SF_COUNT at the RFR server will be desynchronized with RFR client.

In order to verify the synchronization the RFR client sends a GET request for a correctly received BB-frame, immediately after having received the session start acknowledgement. RFR server retransmits the requested BB-frame via LTE network in response to the test GET request. The synchronization between the client and server is confirmed if the retransmitted BB-frame is the same as the one requested. In the case of detecting a desynchronization, the RFR session can be started again for the same PLP.

RFR session change

If a smartphone switches to a different DVB service or starts getting low data rate version of the same DVB service, it has to switch to a new PLP. To switch to a new PLP the RFR application in the smartphone makes a session close request for the current PLP. As the session closure is acknowledged, the RFR application in the smartphone requests a new RFR session for repairing the newly switched PLP. In Figure 5.8, the RFR application is shown closing an RFR session for PLP_0. After receiving a session closure acknowledgement it starts an RFR session for PLP_61. It can be noticed that at the start of a new session the SF_COUNT is reset.

5.5 LTE Round Trip Time (RTT) Latency effects on the RFR service

We consider the experimental test results presented in [78] and the simulation results from [79] for a quantitative understanding of the proposed RFR procedures.

A LTE User Equipment (UE) is in two possible states: in ECM-connected or ECM-idle state. Generally, a UE is in ECM-idle state, when it has not exchanged any signaling with the LTE network for a while. When a UE accesses the network for the first time after being in ECM-idle state, the access delay includes state transition time also along with the random access delay [80]. For a release 10 compliant UE the maximum allowed transition time from idle to the connected state is 50 ms [81].

According to the experimental test results shown in [78], the downlink end to end time delay is on average 6 ms. The experiments were conducted for a 5 MHz LTE system and a UDP packet length of 1250 bytes i.e. 10000 bits. The delay value was obtained for the case when there are no Hybrid Automatic Repeat reQuest (HARQ) retransmissions. For one time HARQ retransmission the downlink latency is increased to 14 ms on average for the same UDP packet size. Since CoAP is also UDP based, therefore we can use the results in our analysis. A BB-frame varies from 7032 bits to 13152 bits[26]. Thus each BB-frame can be transmitted as one UDP datagram.

In [79] authors propose two new variants of the classical scheduling and resource allocation algorithms. In their simulation work they consider a 5-MHz LTE system. They include some results with the classical schedulers also. We choose the results for the classical Proportional Fairness (PF) scheduler. The considered delay value for a PF-scheduler is 42 ms on average for 144 users per cell and a minimum throughput of 200 kbps.

Using the considered end-to-end uplink and downlink delays, we then deduce a maximum RTT delay of 106 ms ($50 + 42 + 14$ ms) for the LTE network. This time includes the time for making a CoAP request via LTE uplink i.e. 42 ms, the 14 ms maximum delay for receiving the CoAP response through LTE downlink and 50 ms of the state transition time. The CoAP CON messages timeout should be dimensioned either equal to or longer than 106 ms. (150 ms considered).

The typical duration for a DVB-T2 frame is 200 ms and typically a superframe has two T2-frames [59]. In Figure 5.4.2 the SF_COUNT is reset with the start of a new RFR session. If the time for the session start request (i.e. SF_COUNT reset request) to reach the RFR server is longer than a superframe time period then the value of

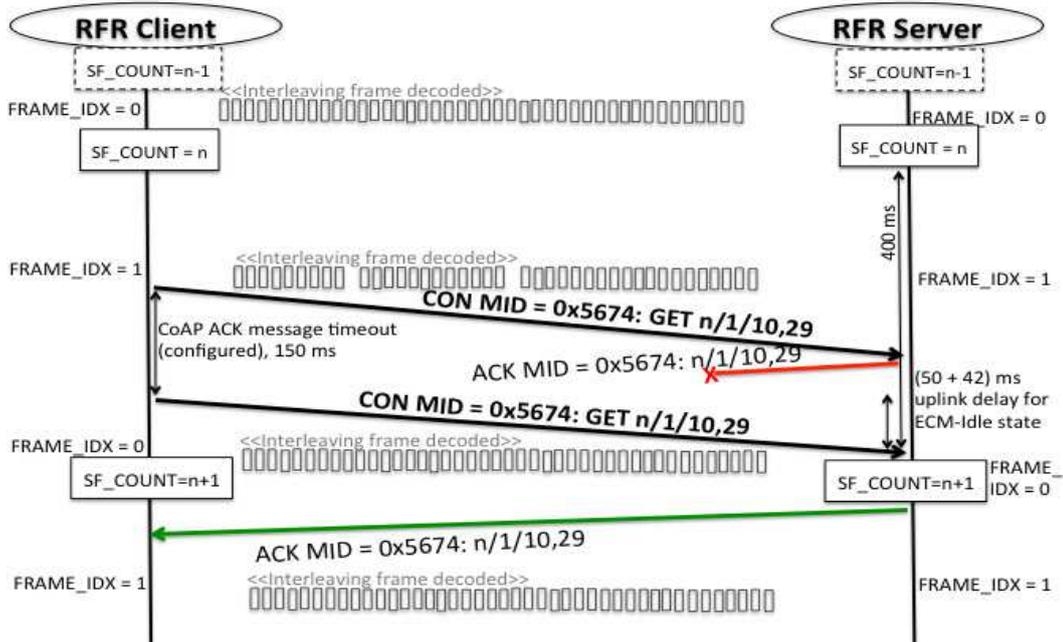


Figure 5.9: RFR SF_COUNT rationale

SF_COUNT between the client and server may differ. As a T2-frame is typically 200 ms and superframe comprises two T2-frames[59] long, thus a superframe is typically 400 ms long. Since the maximum end-to-end uplink delay (i.e. 50 ms + 42 ms) is much smaller than the typical time period of a superframe, therefore the probability of desynchronization is low. Moreover, the proposed synchronization test gives an additional protection against any possible desynchronization.

In Figure 5.9 we depict an RFR session associated to a specific PLP. In the considered scenario no BB-frame was lost till SF_COUNT = $n - 1$ and the value of $n - 1$ is large enough to consider UE in ECM-idle state. Given there were no other exchanges between UE and the LTE network, we take the UE i.e. smartphone to be in ECM-idle state.

In the last T2-frame of the n^{th} superframe two BB-frames are lost. The RFR client sends an RFR request in the confirmable CoAP message to get those two missing BB-frames retransmitted. The total delay budget of sending a CoAP retransmission request via LTE uplink is 92 ms, for a UE in ECM-idle state. We show that the acknowledgement along with the requested packets doesn't arrive at the RFR client within the pre-configured timeout(i.e. we assume 150 ms). As the timeout duration passes, the client relaunches the same request. The response to the second attempt is successfully received by RFR client (i.e. smartphone).

In the illustrated example the total time taken by the LTE network to retransmit the lost BB-frames is 256 ms (i.e. $150 + 106$ ms). The RFR client receives the missing BB-frames when the DVB decoder is reading the next superframe i.e. $n+1$. Thanks to the SF_COUNT field the RFR client is able to relate the received BB-frames to the relevant superframe and avoids a possible error in the buffer, while putting the retransmitted packets in the right sequence.

5.6 RFR Server Location

5.6.1 Evolved Packet System

A cellular network architecture is divided into the Radio Access Network (RAN) and Core Network. In the name of System Architecture Evolution (SAE), an evolved architecture for the LTE core network was proposed, which is called Evolved Packet Core (EPC). Along with a new architecture for the core, a flat architecture for RAN was also proposed. The new RAN and EPC together are called Evolved Packet System [5, 82].

The main LTE EPC function is to route the data traffic between RAN and Packet Data Networks (PDNs). Normally, the PDNs are IP networks. One of the key feature of the EPC is the architectural segregation of the user traffic from the control signaling [83, 84, 85]. The part of EPC bearing user traffic is referred as user plane. In the LTE EPC 's user plane there are two gateways. Logically both gates are connected to each other [83] inside the EPC, whereas outside EPC each of them is interconnected to a different kind of network. These two gateways are:

- Packet Data Network Gateway (PGW): The PGW is the entry and exit point for the user data traffic from the PDN into the LTE EPC. A PGW allocates IP address /IP prefixes and also manages policy control and charging [86]. The PGWs are very few in number.
- Serving Gateway (SGW): It serves as a packet forwarding entity between the LTE RAN and LTE EPC. A SGW is connected to several eNodeBs and as mentioned in [5], it serves as a mobility anchor for the UE during an inter-eNodeBs or an inter-3GPP technology (GSM, UMTS etc) handover.

5.6.2 EPS bearer

A bearer is a path for the data transmission across a LTE EPC with a defined priority, capacity, delay and packet loss rate [82]. A bearer basically signifies the way a network treats data. The network's treatment with a given data flow depends on the values assigned to the parameters of the bearer. The choice of parametric values depends on the QoS required by the service.

The establishment of a bearer signifies having a logical connection between the UE and the PDN across the LTE EPC. A UE is assigned a 'default bearer' when it connects to a PDN. A default bearer may carry any data traffic as per the interest of the user. A default bearer carries an IP address incase if the PDN is an IP network. It is by virtue of that IP address UE is able to use the available services in the relevant PDN e.g. web browsing and email etc.

5.6.3 RFR servers enabling a joint infrastructure

The basic function of an RFR server is to retain all the BB-frames from a DVB transmission at the disposal of an RFR client located anywhere in the cellular network. Thus an RFR is essentially required to be linked to both of the considered infrastructures i.e. a DVB-T2 system and a LTE EPC. In our work the RFR servers are the foundation of a joint infrastructure shared by both networks i.e. DVB and LTE networks. We consider three kinds of RFR servers:

- National RFR server
- Regional RFR server
- Town level RFR server

National RFR server

The terrestrial DVB network is a single nation network. Thus, there is one T2-gateway (as shown in Figure 2.3) placed in the heart of a T2-system. A national RFR server is directly connected to the considered T2-system. A DVB transmission is available in a pre-transmittable form at this level (i.e. T2-Modulator Interface (T2-MI) stream ¹). We assume the RFR server to be capable of extracting the DVB transmission like a T2-modulator (Figure 2.3). On the other hand, a LTE EPC is also centralized around

¹A T2-MI stream packet contains a BB-frame with the scheduling and synchronization information for its transmission through a DVB-T2 transmitter

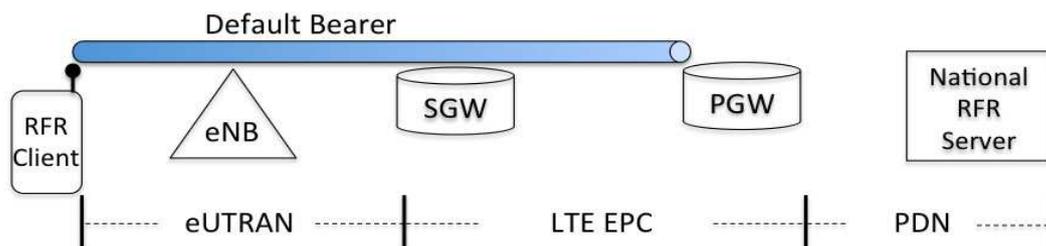


Figure 5.10: National RFR Server

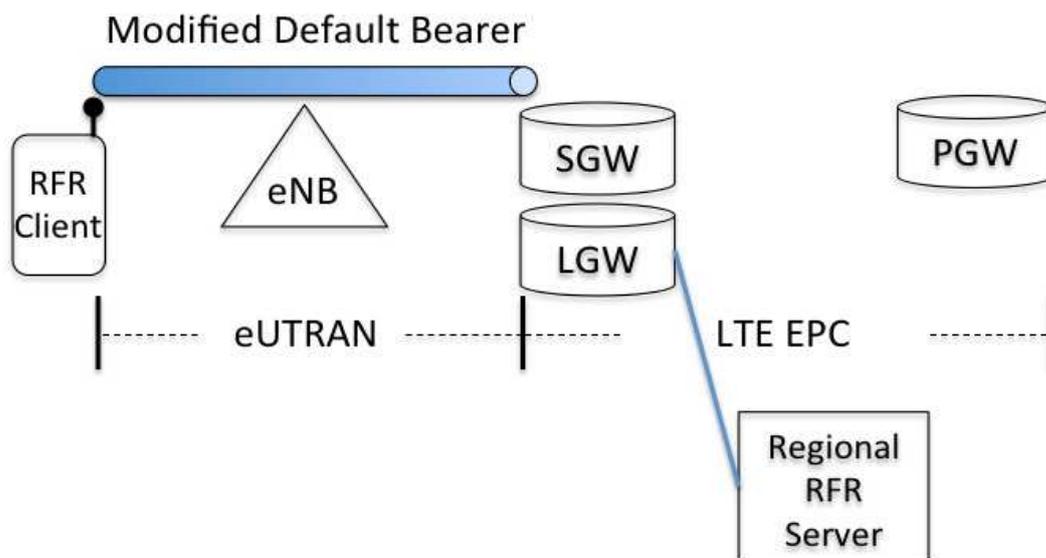


Figure 5.11: Regional RFR Server

a PGW. We consider that a national RFR server is hosted in the corresponding PDN. A national RFR server entertains the queries from any part of the cellular network and retransmits the requested BB-frames by extracting them from the T2-gateway. This kind of solution is simple to implement as a national RFR server can be owned by any stakeholder including: network operator, broadcaster or a third party. The retransmission of BB-frames has the same RTT delay as determined in Section 5.5. In Figure 5.10 we illustrate a simplified scenario where the national RFR server provides a service via default EPS bearer.

Regional RFR server

In a T2-system the insertion of a regional transmission is possible. The PLP carrying a regional transmission is identified by the CELL_ID, which identifies the DVB cell of the content's origin. In such case an RFR request has to be directed to a regional RFR server.

In order to enable the insertion of the regional content over some PLPs in the DVB transmission there are some regional T2-gateways which include some additional streams on the reserved PLPs prior to the dissemination of the DVB transmission data among the T2-modulators in a region (refer to Figure 2.3). By function a regional RFR server is same as a national RFR server. The deployment of a regional RFR server is subjected to the presence of a regional T2-gateway.

An advantage of having a regional RFR server is the possibility of a faster repair operation. There is a small number of PGWs compared to the number of SGWs in the LTE EPC. Therefore it is more probable for a regional T2-gateway to be in the close proximity of a SGW. For the 3GPP release 10 and advanced mobile phones it is possible to have a default bearer from an IP network (e.g. Internet) via the closest Local-Gw (LGW) using SIPTO technique. Generally, a LGW used SIPTO is co-located with a SGW. However, a LGW located in the LTE access network can also be selected for offloading data traffic using SIPTO [87, 88].

In our work we consider SIPTO technique to offload the RFR clients at a LGW co-located with the SGW. Figure 5.11 presents a simple illustration of the regional RFR service via default bearer. The default bearer is modified within the EPC to offload the RFR client by re-selecting the LGW/SGW.

We assume a regional T2-gateway connected to a regional RFR server which is hosted in a PDN to which any RFR client (i.e. a smartphone) is offloaded via SGW. In such case the RTT delay is shorter. In the presence of a regional T2-gateway an RFR request should preferably be offloaded to a regional RFR server. Because a regional T2-gateway also contains the T2-MI packets of the national transmission.

Information about the identities of the PLPs carrying regional content is not known to a DVB receiver. A DVB receiver only has the information about the presence of the regional content in the DVB transmission by reading the CELL_ID in the signaling preambles. However an EPC can extract the identities of the PLPs carrying regional content by probing the regional T2-gateway via regional RFR server. Thus the excessive signaling load due to SIPTO offloading can be controlled by routing the RFR requests for the national programs to the national RFR server even if a regional RFR server is available. The LTE protocol stack does not change for a SIPTO technique based connection to the regional T2-gateway. Therefore, the described repair procedural steps in Section 5.4 are valid for the regional RFR server based repair as well.

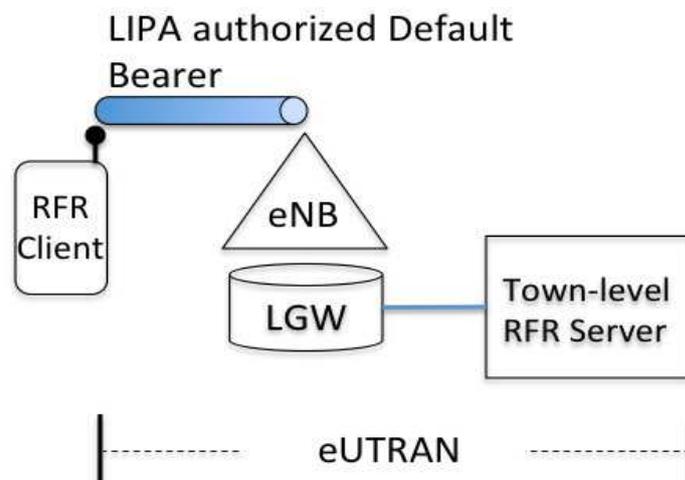


Figure 5.12: Town-level RFR Server

Town-level RFR Server

Apart from a national or a regional RFR server, a town-level RFR server can also be foreseen. This possibility can be considered as a futuristic aspect of our proposal, which depends on the popularity of the RFR service. The precondition for such an RFR server is the large presence of the RFR clients in a town so that an operator decides to deploy an RFR server in the RAN (i.e. eUTRAN). Such RFR server can interact with all the eNodeBs in the eUTRAN using the LIPA technique.

The LIPA technique is originally proposed for the scenario where a Home eNB (HeNB) is co-located in a residential/ enterprise Local Access Network (LAN) with a LGW. This technique enables a UE to access any entity in the LAN, without the user plane traversing through the LTE EPC. We extend the concept of LIPA for macro cells by considering a LGW co-located with each eNB. Thus we consider a town-level RFR server in a LAN which includes several eNBs with LGWs. The use of LIPA is subjected to the registration, authentication and authorization of the UE and the eNB by the LTE EPC [87]. In Figure 5.12 we illustrate a town-level RFR service operating via LIPA authorized default bearer.

This kind of RFR server is not connected to the T2-system infrastructure except it receives the same DVB transmission as any DVB receiver but at a roof-top height in the QEF conditions. This solution permits the fastest recovery of the missing BB-frames from any PLP transmitted by the DVB transmitter in the given locality. However, such installation of an RFR server is subjected to strict corporate contracts with the operators as in the previous two cases it was relatively easier to have a cable link to the T2-system entities. Those servers can be owned by Broadcasters/operators/ any

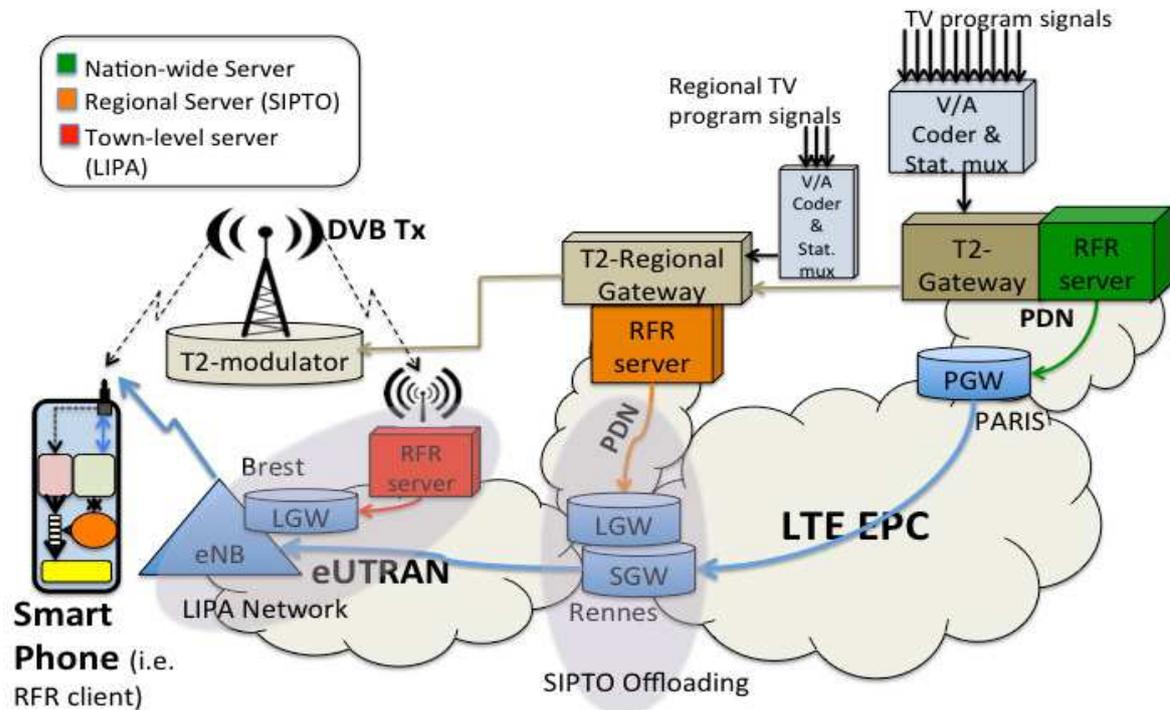


Figure 5.13: RFR servers integrated into the LTE core network and the DVB-T2 System

third party, like any other IP network server. In the case of a town level, an operator has the maximum leverage because the RFR server is proposed to be stationed in the access network.

Example to illustrate the DVB-LTE joint infrastructure

In Figure 5.13 we take the example of an operator's LTE core network with the PGW deployed in Paris for the entire France. Since a DVB terrestrial network is a single nation network, therefore we consider a central T2-gateway also stationed in Paris. We consider a regional T2- gateway for the Bretagne region in Rennes which inserts some regional content on some of the PLPs of the DVB T2-transmission. We assume that this regional gateway is in a close proximity to a SGW. Thus we consider a SGW situated in the regional capital Rennes, serves as a point where the RFR users seeking the repair for a regional DVB transmission are offloaded using SIPTO technique. For a town-level RFR server we assume a wide base of users willing to pay for the RFR service in Brest. Thus the operator decides to deploy a Town-level RFR server connected to the several eNodeBs covering Brest.

5.7 Summary

This chapter presents the core proposal of the thesis work i.e. the Real-time Flow Repair (RFR) service to the smartphones. In this chapter we give the concept of a real-time repair over the broadcast data flows through LTE network. In our work we concentrate on three relevant aspects of a Realtime Flow Repair service, which include, availability of the cellular network resources, identification of the broadcast data flow packets and a fast retransmission of the missing elements via cellular network. A realtime flow repair service is possible thanks to a light application protocol i.e. CoAP, which is a client-server protocol. Although in the specific case considered we focus on the DVB-T2 as the broadcast technology but we believe that the role of a broadcast system is possible to be played by any technology capable of broadcasting high quality multimedia transmission to the smartphones.

We consider a mutually coordinated infrastructure for the LTE EPC and DVB-T2 system which enables a smooth implementation of the proposed RFR service. The procedures defined for an RFR server are independent of the position of an RFR server in the coordinated infrastructure. As the deployment of SIPTO and LIPA techniques does not affect the LTE protocol stack. An advantage of offloading RFR subscribers to a regional or a town level RFR server is enabling shorter RTT delay for the repair operation, which further enhances the real-time aspect of the proposed RFR service.

DVB retransmission load over LTE network

As already discussed in Chapter 3, a DVB network is designed to cover fixed receivers. The link budget for the handheld receivers is weaker compared to the fixed receivers. Thus the handheld receivers suffer a higher outage compared to the fixed receivers. In our proposition, the cellular network helps in reducing the DVB handheld outage by retransmitting the missing BB-frames to the handheld receivers. In this chapter we analyze the load over the LTE access network due to the retransmission of the missing BB-frames of a given PLP. A straightforward solution to overcome the DVB handheld outage is to increase the DVB transmission power [89]. We determine the amount of transmission power which can be saved in the DVB network for an acceptable level of the load over the LTE network. We analyze the load generated in the LTE network for different Inter-Site Distances (ISD) in the LTE network (i.e. among eNode Bs (eNBs)).

In section 6.1 we explain a scenario where the hexagonal layouts of the DVB and LTE network cover the same geographical location. Section 6.2 presents a brief synopsis about the concept of resource allocation in a LTE network. In section 6.3 we develop an approximate BB-Frame error performance model for the DVB-T2 FEC coding chain. We determine the LTE network loading in terms of LTE resource parameters i.e. Pairs of Resource Blocks (PRBs) per Transmission Time Interval (TTI). Section 6.4 gives the parametric values for the considered scenario and some discussion about the proposed cooperative interworking between the two networks in the light of the simulation results. Finally section 6.5 summarizes the simulation results and highlights the significance of the results in the context of the thesis work.

6.1 Preliminaries

6.1.1 Fundamental Configuration

We consider a geographical area covered by both DVB and LTE networks. We assume that there are n_{eNB} eNBs in a DVB cell, each eNB covers a single LTE cell. Hence,

$$A_{DVBcell} = n_{eNB}A_{LTEcell}, \quad (6.1)$$

where, $A_{DVBcell}$ and $A_{LTEcell}$ are the areas of a DVB cell and an LTE cell respectively. This implies that the radius of the DVB cell R is related to the radius of the LTE cell R_{LTE} as,

$$R = \sqrt{n_{eNB}}R_{LTE}. \quad (6.2)$$

At the centre of the DVB cell, there is a DVB transmitter at a mast height of h_{DVB} in meters. The considered transmitter is surrounded by six neighboring transmitters equidistant from the central DVB transmitter. All DVB transmitters are at the same height. The considered DVB transmitters form a SFN (consider (2.1)). By assuming the hexagonal shape of the DVB cells we relate the radius of each cell, R , to the ISD, D_{DVB} km as,

$$R = \frac{D_{DVB}}{\sqrt{3}}. \quad (6.3)$$

For n_{eNB} LTE cells there are n_{eNB} eNBs with omnidirectional antennae covering the DVB central cell's area as shown in Figure 6.1. Each eNB has an antenna height of h_{eNB} . We assume all the LTE cells to be of the same size. We assume a uniform population density of ρ per sq. km in the central DVB cell. All the handheld receivers have a height of h_r in meters. We consider a high definition DVB TV transmission, which is supposed to provide a per-user data rate of r_{user} Mbps. We suppose that only $p\%$ of inhabitants of the total population are watching a TV program, via the same PLP, and that there are n_{NO} mobile network operators each having an equal subscriber base. Therefore, the effective population density of a typical mobile network operator users watching the TV program at the same time is, $\rho_{eff} = \frac{p}{100n_{NO}}\rho$ per sq. km. In Figure 6.2 the uniformly distributed DVB handheld receivers, the positions of the eNodeBs and the DVB transmitters can be seen.

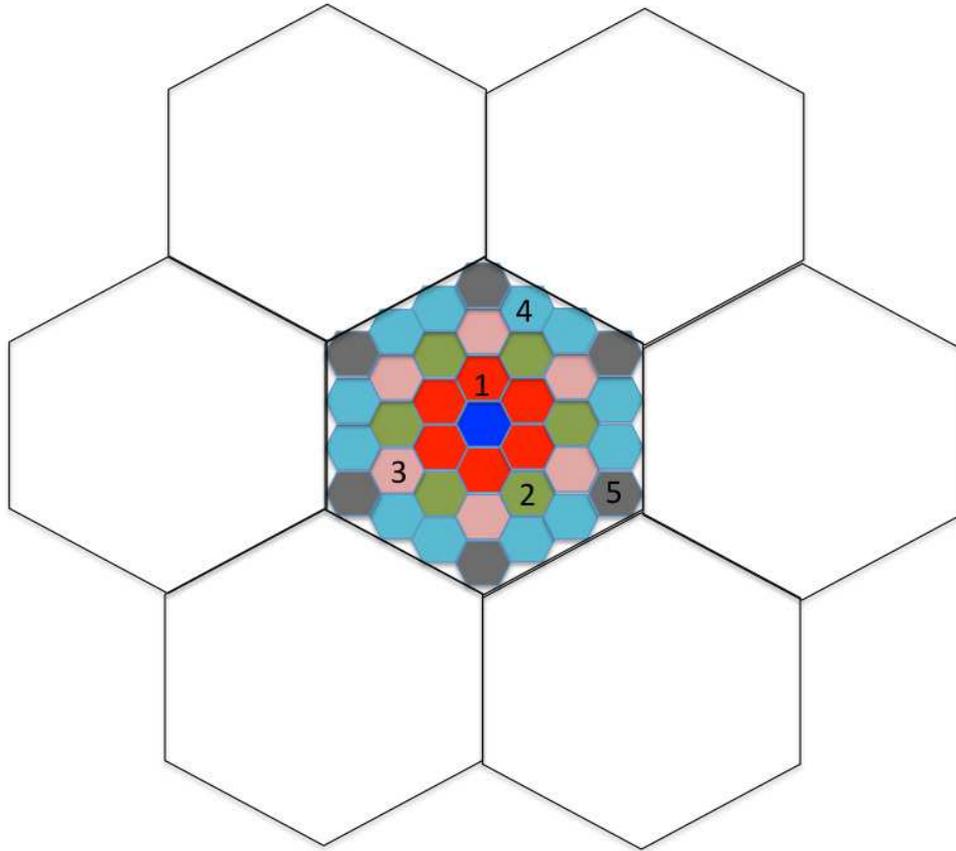


Figure 6.1: DVB vis-a-vis LTE deployment considered

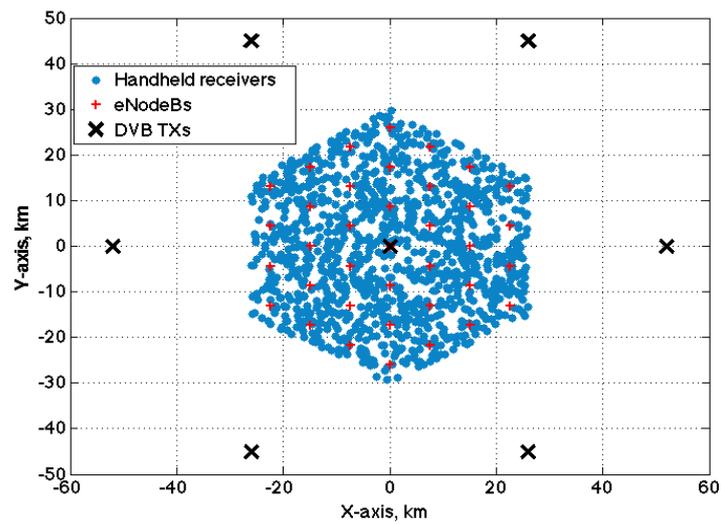


Figure 6.2: Central DVB cell: Handheld 's placement

6.1.2 Propagation Model

Path-loss model

For DVB and LTE signal propagation, we use the Okumura-Hata model. Basically, this model was proposed for cellular network average path-loss calculations, but it is also common to apply it on DVB networks e.g.[32]. According to the Okumura-Hata model[90], the average path loss in urban environment is given as in (2.6).

Shadow fading

We consider the shadow fading for each eNB's radio links to users, to be correlated with the radio links of the neighboring eNB, as shown and explained in (2.7) from Chapter 2.

We take $\sigma_o = 5.5$ dB for the DVB network [7] and for the LTE network we take $\sigma_o = 6$ dB and $\chi = 0.5$ [6, 34, 90].

Received Power

The model for received power of the DVB signal and Noise power are the same as considered in (2.9) and (2.10).

We assume an integrated antenna in the handheld receiver, which receives both signals, i.e. DVB and LTE signals. The correction in the receiver antenna gain for a given signal frequency f_a w.r.t. the reference frequency of the antenna, f_r [7] is given by,

$$Corr = 10 \log \frac{f_a}{f_r} \quad (6.4)$$

We assume the LTE signal frequency to be the reference frequency for the integrated handheld receiver antenna i.e. 2100 MHz [6]. At the reference frequency, f_r , let the handheld receiver gain be 0 dBi (i.e. -2.14 dBd). Hence, for a 650 MHz DVB signal, the handheld receiver gain G_{iso} is - 5 dBi.

Interference in the LTE network

Each user at a given time is associated with only one eNB, therefore the power received by the receiver from the rest of the eNodeBs interferes with the desired signal. Hence, there are $n_{eNB} - 1$ number of interference sources in the LTE network for each handheld receiver. For a user in the k^{th} LTE cell the SINR can be given as,

$$SINR = \frac{P_{s,k}}{N_0 + \sum_{i=1 \rightarrow n_{eNB}}^{i \neq k} P_{s,i}}. \quad (6.5)$$

6.2 LTE Resource Allocation

The LTE OFDM signal transmissions are arranged in OFDM frames called 'subframes'. A subframe is the fundamental resource allocation unit for an LTE scheduler. Each sub-frame consists of two resource blocks. Each resource block is strictly spread over 0.5 ms. A resource block has 180 kHz wide bandwidth comprising twelve subcarriers, with a subcarrier spacing fixed at 15 kHz.

The timing for any LTE physical resource is a multiple of the OFDM sample time, $T_{sample} = 1/(\text{sub-carrier spacing} \cdot \text{FFT size})$, where the FFT size for the OFDM modulation of the LTE signal is 2k at maximum. The useful OFDM symbol duration is the reciprocal of the sub-carrier spacing i.e. $66.7\mu\text{s}$. Each OFDM symbol includes a cyclic prefix, which is the cyclic repetition of the useful part of an OFDM symbol. Each resource block generally comprises 7 OFDM symbols, as shown in Figure 6.3.

A resource element is the smallest physical resource in a LTE network. It consists one subcarrier during one OFDM symbol [5]. The resource element is called an OFDM cell in the vocabulary of DVB transmission resources. Thus a resource block consists of 84 resource elements (i.e. 12×7) (see Figure 6.3).

There are 10 subframes in a LTE radio Frame. Each frame is identified by a Frame Number in the LTE transmission. The time duration of a subframe is also called Transmission Time Interval (TTI) which is fixed as 1 ms. In LTE network a given subcarrier is allocated to a User Equipment (UE) for the entire TTI. Thus depending on the bandwidth requirement and the scheduling decision several subcarriers are allocated to one or several UEs during each TTI. Therefore the available capacity in the LTE network is considered in terms of the Pairs of Resource Blocks (PRBs) per TTI. Thus 20-MHz bandwidth can also be expressed as 100 PRBs per TTI. The LTE network capacities for different standardized bandwidths are given in Table 6.1.

The LTE scheduler allocates bandwidth to a UE in terms of the number of PRBs per TTI. In Figure 6.4 we present a simple illustration of the bandwidth allocation to several UEs in a LTE radio frame. Each UE is identified by a Temporary identifier allotted by the LTE network.

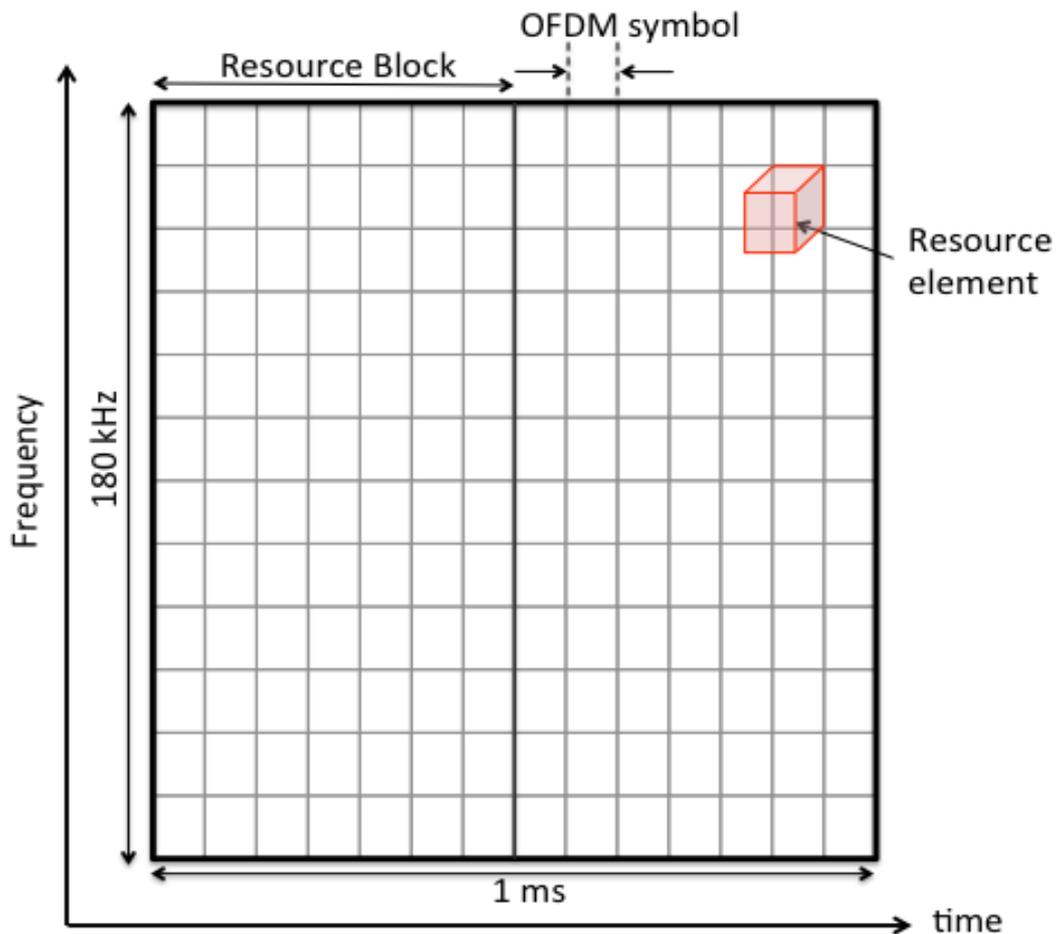


Figure 6.3: The composition of a LTE subframe

Table 6.1: LTE Network Capacity for different Bandwidths [4]

Bandwidth	1.4	3	5	10	15	20
PRBs per TTI	6	15	25	50	15	100

6.3 DVB Transmission Power and Loading of the LTE network

In this work we propose a basic model of cooperation between the DVB and LTE networks. In our scheme we use the LTE network for the retransmission of the missing BB-frames at the UE, which are lost due to the packet loss in the DVB transmission to

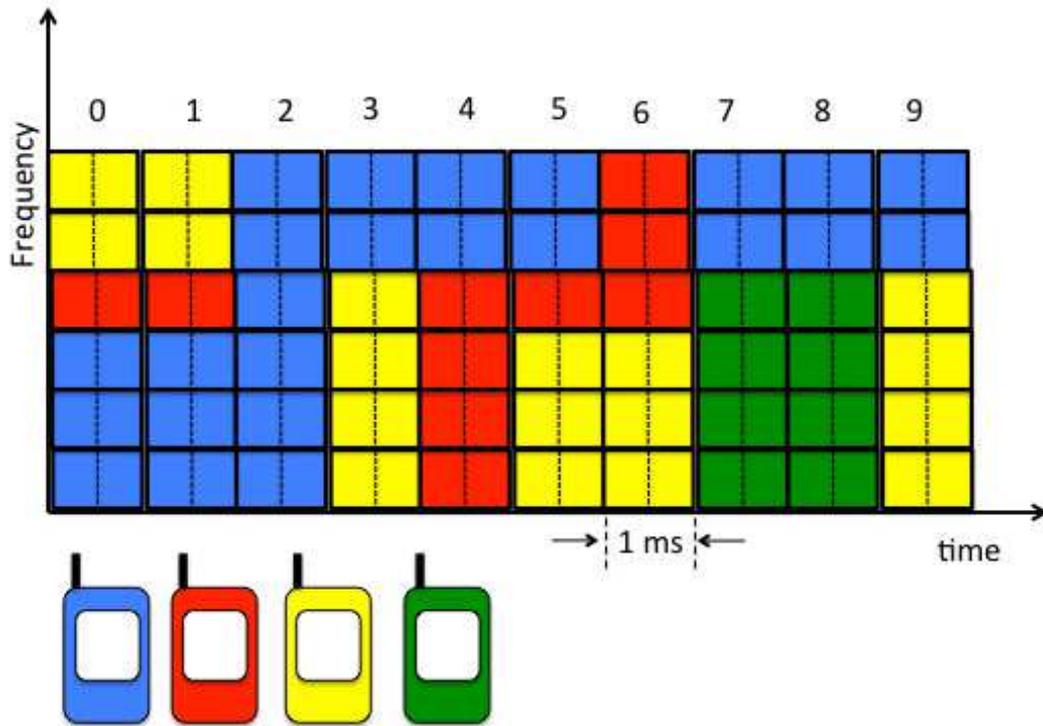


Figure 6.4: LTE bandwidth Allocation

it. In this section we try to establish the relationship between the DVB transmission power and the load over the LTE network.

6.3.1 Load Evaluation

We consider a sigmoidal curve based error performance model which gives Bit Error Rate (BER) for a given SINR of the DVB radio link. The error performance function developed is,

$$BER = 1 - \frac{1}{1 + e^{a_1(SINR)^2 + a_2(SINR) + a_3}}, \quad (6.6)$$

where a_1 , a_2 and a_3 are the parameters having specific values for a considered modulation and coding scheme. Details about the error performance model can be found in Appendix B. Our scheme takes into account the BB-frames in error, therefore for a BCH code's hamming distance, d_h , and b_{fr} bits per BB-frame, the Frame Error Rate, FER , can be approximated as,

$$FER = BER \frac{b_{fr}}{d_h} \quad (6.7)$$

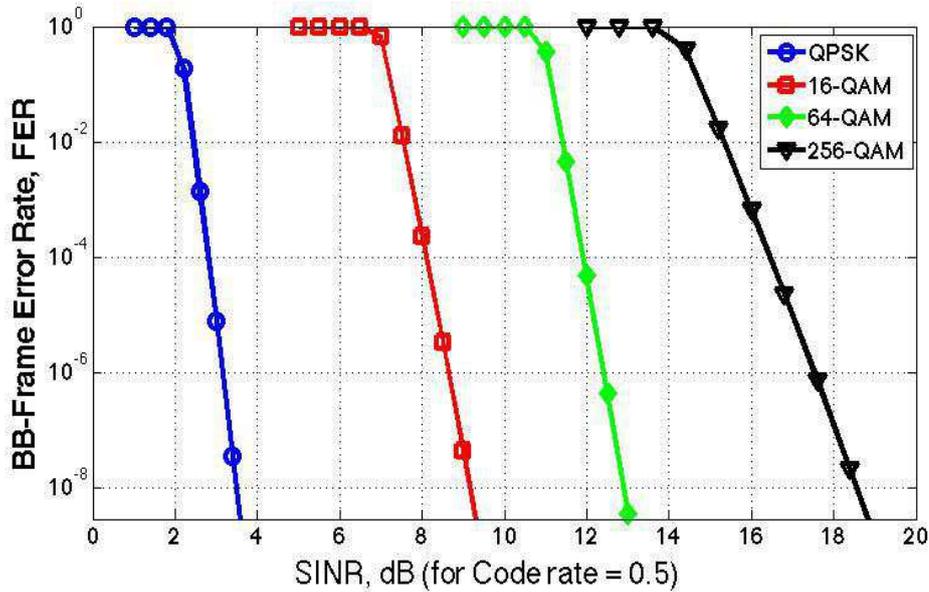


Figure 6.5: FER performance curves for DVB-T2 data signals

Table 6.2: Values for the parameters of the BER model

Modulation Coding Scheme	a_1	a_2	a_3
1/2 QPSK	-0.67	-9.2	16.2
1/2 16QAM	-0.27	-3.94	34.75
1/2 64QAM	-0.27	-2.76	56.37
1/2 256QAM	-0.082	-1.51	32.18

For a detailed discussion related to this approximation, we refer the reader to [91]. In Figure 6.5, we plot the DVB-T2 FER performance curve for the data signal by using (6.6) with (6.7). The values of a_1 , a_2 and a_3 used for the given modulation coding schemes are listed in Table 6.2. We consider 1/2-16-QAM for the DVB signal to the handheld receivers, which is optimal from both coverage and capacity points of view [7].

We know that a BB-frame is the logical unit data packet of a DVB transmission. We consider a short FEC frame size i.e. 16200 bits to conform with the T2-lite profile [26]. We developed FER model for 1/2 code rate, which is effectively 4/9 for a short FEC frame due to LDPC coding limitations. The corresponding size of a BB-frame is 7032 bits (i.e. $\frac{4}{9}16200 - 168 = 7032$), where, the number of parity bits for the BCH encoding is 168 bits, Table 6(b) of [1]. This makes an equivalent data rate of 73 BB-frames/sec for $r_{user} = 0.512$ Mbps, which is the source data rate of a high definition multimedia service for the handheld receiver [92].

Using the model presented in (6.6) we compute the FER for a given user against the SINR of the DVB signal. By multiplying the FER for that user with $\frac{r_{user}}{b_{fr}}$, we get the number of erroneous BB-frames to be retransmitted by the LTE network for that user. The retransmissions of BB-frames summed for all the users in an LTE cell gives the total number of BB-frames lost per second per eNB, $Load_{eNB}$.

$$Load_{eNB} = \frac{r_{user}}{b_{fr}} \sum_{i=1 \rightarrow n_{percell}} FER_i, \quad (6.8)$$

where, $n_{percell}$ is the number of users per LTE cell.

6.3.2 Number of the Pairs of Resource Blocks

In [93] the authors have used the Shannon capacity formula to fit over the simulation results for various multiantenna and multiuser scheduling configurations of the LTE air interface. They introduced two variables, i.e. Bandwidth Efficiency and SINR efficiency, in the Shannon formula. We have considered the link-level fit for a SISO (1x1) Downlink antenna configuration, TU-6 channel and Round Robin-based packet scheduling system. For the i^{th} handheld receiver, the spectral efficiency, S_i , as a function of SINR is given as,

$$S_i = 0.56 \log_2(1 + SINR_i/2) \quad (6.9)$$

where $SINR_i$ is the SINR received by the i^{th} handheld receiver in the LTE access network. As discussed in Section 6.2, LTE bandwidth is allocated in Pairs of Resource Blocks (PRB) spread over one Transmission Time Interval (TTI), $t_{TTI} = 1$ ms. Each PRB has a bandwidth of $B_{PRB} = 0.180$ MHz. The number of the PRBs per TTI demanded by a single UE depends on the number of bits of the BB-frames to be retransmitted and the available spectral efficiency. Mathematically, the number of PRBs reserved to repair the DVB transmission for all the UE in a LTE cell can be calculated as,

$$PRB_{eNB} = r_{user} \sum_{i=1 \rightarrow n_{percell}} \frac{FER_i}{B_{PRB} S_i}, \quad (6.10)$$

where FER_i is the FER experienced by the i^{th} handheld receiver.

In Figure 6.6 we illustrate the retransmission of the missing BB-frames via LTE network. We show three UE associated to an eNB, each of the three UE lose one BB-frame after decoding the DVB transmission. An eNB typically selects a high order

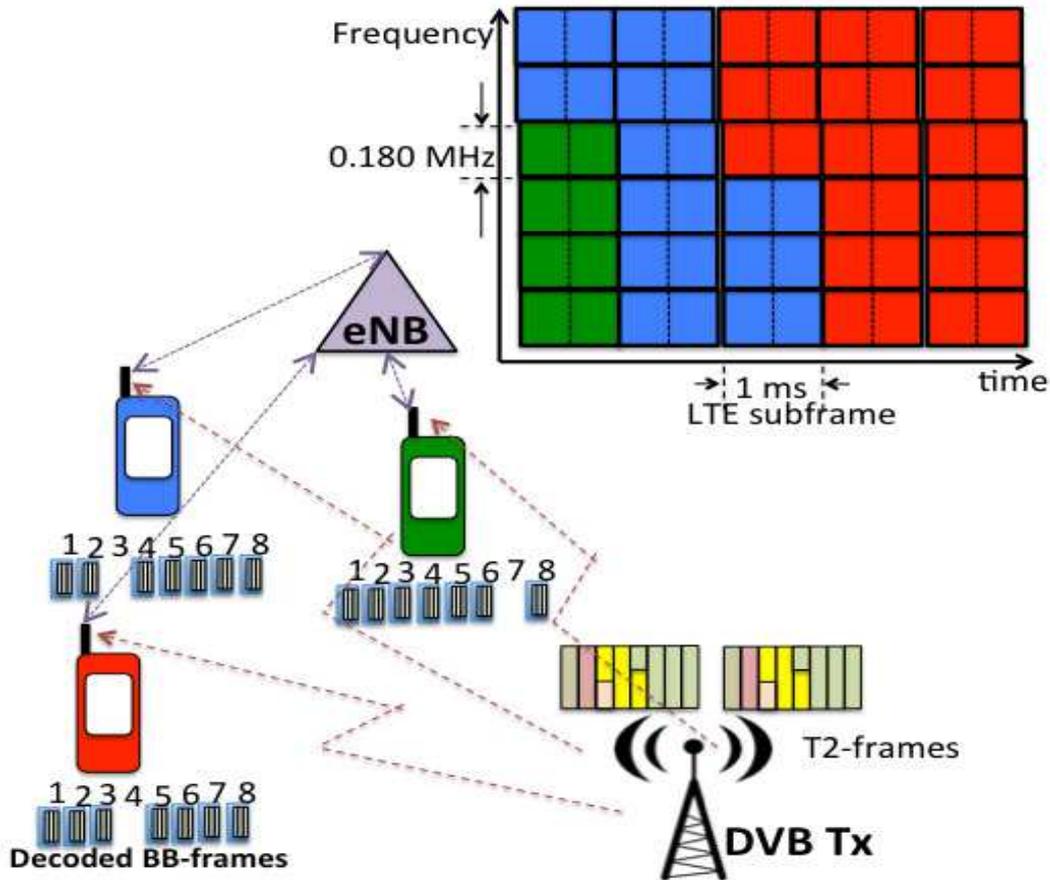


Figure 6.6: Lost BB-frames per sec in terms of PRBs per TTI

constellation for the UEs close to it, thus the users close in distance enjoy better spectral efficiency therefore, in a LTE frame they require fewer PRBs compared to farther ones. We do not consider the scheduling for the retransmission of the BB-frames. We simplify this detail by considering the rate of retransmission to be the same as the rate at which the BB-frames are lost from the DVB transmission. Moreover, we also assume no packet losses for the LTE based retransmission of the BB-frames.

6.4 Parametric values and Simulations

In our simulation we change the DVB transmission power and observe the effect on the per cell loading of the LTE network. We observe the loading in terms of the number of the pairs of resource blocks. We obtain a one-to-one relationship between the DVB transmission power and the LTE resources allocated for complementing DVB transmission. We also have some simulation results taking into account the effect of ISD among eNBs on the mentioned relationship.

Table 6.3: Parametric Values for the DVB SFN

Parameter		Value	Unit
Transmission Power	P_t	61 - 80	dBm
Inter-Site Distance	D	52	km
Guard Interval Fraction	GIF	1/4	-
FFT size		8k	-
Bandwidth	B	7.77	MHz
Noise Figure	F	6	dB
Noise Power	N_o	-99	dBm
Receiver height	h_r	1.5	m
Receiver antenna Gain	G_{iso}	-5	dBi
DVB Transmitter height	h_{DVB}	150	m
Carrier Frequency	f_c	650	MHz
Cross correlation coefficient	χ	0.5	-
Standard Deviation Shadow fading outdoors	σ	5.5	dB
Population density	ρ	100	per sq. km
%handheld TV Program watchers	p	2	-
Number of Mobile Network Operators	n_{NO}	4	-
Effective population density	ρ_{eff}	0.5	per sq. km
PLP per user data rate	r_{user}	0.512	Mbps

6.4.1 Parametric Values

In Table 6.3 and Table 6.4 we present the parameter values used for the DVB SFN network considered and the LTE network respectively.

Table 6.4: Parametric Values for LTE Network [5],[6]

Parameter		Value	Unit
Transmission Power	P_t	49	dBm
eNB antenna gain	A	17	dB
Cell radius	R_{LTE}	1-5	km
Bandwidth	B	10	MHz
Noise Figure	F	6	dB
Noise Power	N_o	-98	dBm
Receiver height	h_r	1.5	m
Receiver antenna Gain	G_{iso}	0	dBi
eNB antenna height	h_{eNB}	30	m
Carrier Frequency	f_c	2100	MHz
Cross correlation coefficient	χ	0.5	-
Standard Deviation Shadow fading outdoor	σ	6	dB

6.4.2 Simulation Results

In Figure 6.7 maximum number of the BB-frames per second for a user in a LTE cell is considered. The mentioned number is plotted against the distance of the serving eNB from the central DVB cell. The results can also be considered as the total load over the eNB because the population density of handheld receivers receiving DVB transmission is 0.5 per sq. km, whereas the mentioned results are considered for $R_{LTE} = 1$ km. Thus there is on average one user per eNB.

In Figure 6.8 the LTE access network bears a load of 10 PRBs per eNB per TTI which makes 20% of the total capacity and the DVB transmission power can be reduced from 72 dBm to 68 dBm, which saves 9500 Watts.

Similarly, in Figure 6.9, where $D_{LTE} = 5.2$ km, the same amount of power can be saved at the expense of 10% of the available PRBs per TTI per eNB, i.e. 5 PRBs per TTI per eNB. Also if 50% PRBs per TTI per eNB are reserved for the retransmission of the DVB missing packets, we can cover all the handheld receivers in the central DVB cell. This is achievable for LTE $D_{LTE} = 5.2$ km and for a DVB SFN transmission power of 60 dBm. According to our scheme we will have a zero-loading over the LTE access network if the DVB transmission power is 72 dBm. For a DVB transmission power of 60 dBm we save 15kW at each DVB transmitter, which is a significant power

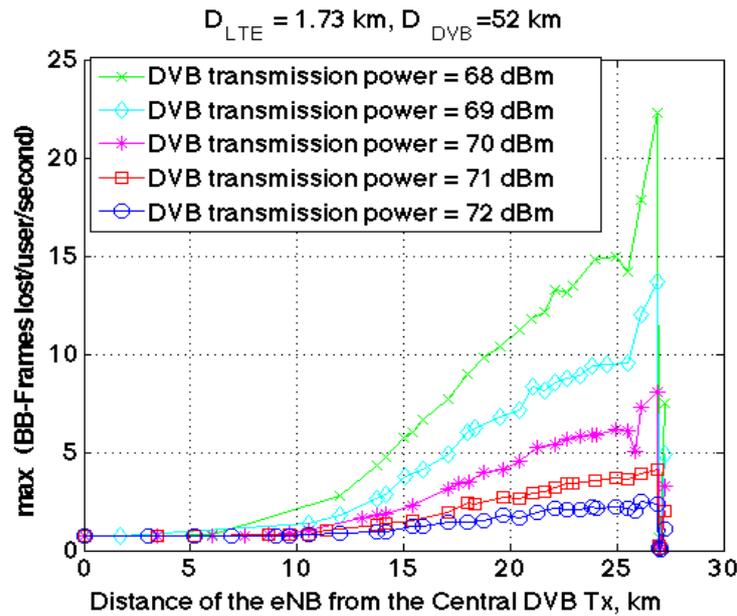


Figure 6.7: Max number of lost BB-frames per second per user for given distance of eNode B

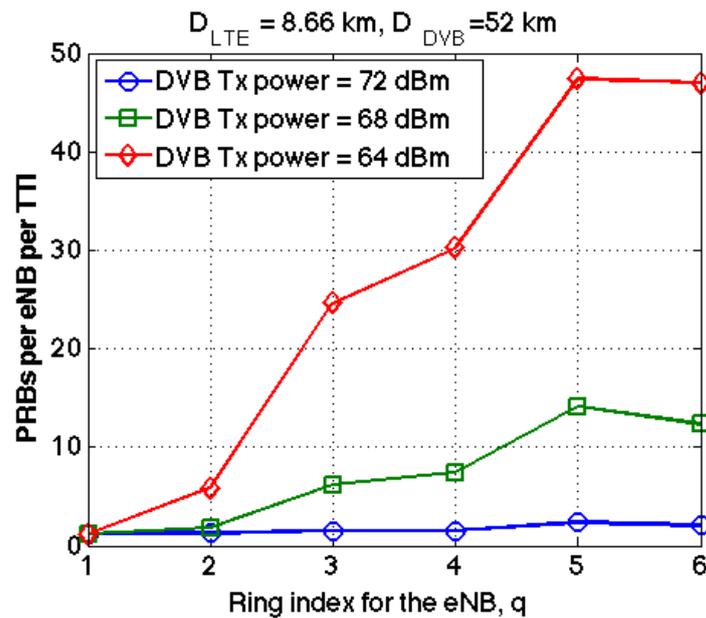


Figure 6.8: PRBs per eNB per TTI vs eNB ring index, for $D_{LTE} = 8.66$ km

saving. The power saving can also be converted into the amplifier cost reduction, as for 12 dB smaller amplification gain reduces the cost of amplifier by 16 times.

In Figure 6.10, it can be observed that for 48 dBm transmission power, the number of PRBs per eNB per Transmission Time Interval (TTI) is under 3 for $D_{LTE} = 1.73$ km. There are 81 equidistant rings of eNBs from the central DVB transmitter. The average load per TTI over each eNB from 20th to 81st ring is under 6 % of the available

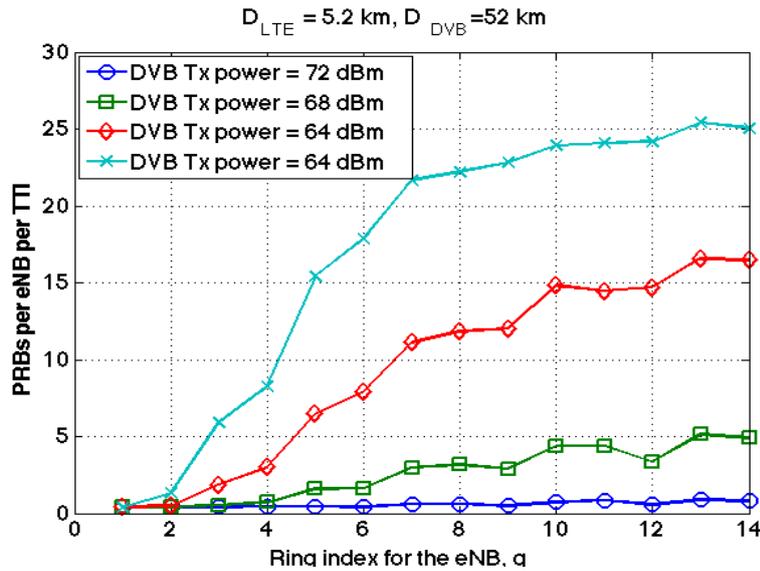


Figure 6.9: PRBs per eNB per TTI vs eNB ring index, for $D_{LTE} = 5.2$ km

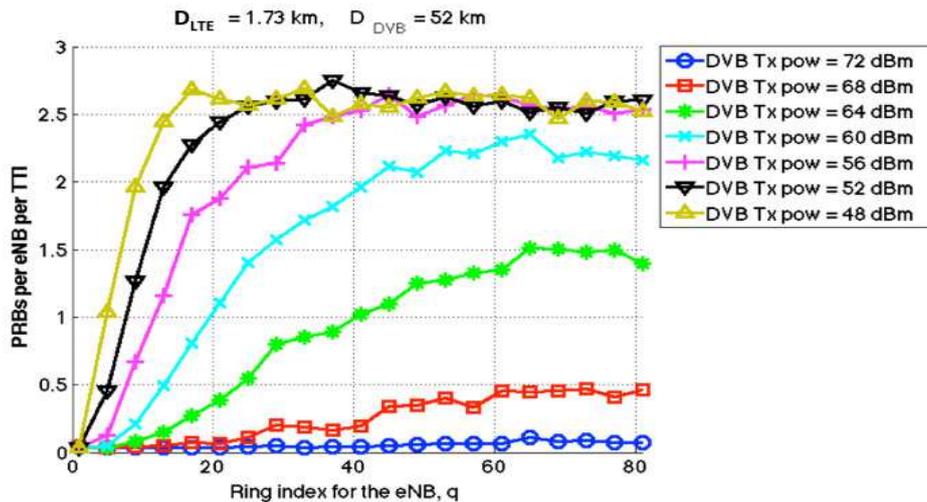


Figure 6.10: PRBs per eNB per TTI vs eNB ring index, for $D_{LTE} = 1.73$ km

capacity. Even though the cell size of $D_{LTE} = 1.73$ km is the smallest among the considered cell sizes, it is still a large cell size compared to the typical LTE cell sizes [5].

For different ISDs we have different number of rings of eNBs in the same central DVB cell area. For example, if $D_{LTE} = 8.66$ km, then there are five rings such that the distance of the 5th ring is the closest to the DVB cell radius. If we divide each ring distance by the DVB cell radius we get the fractional distance of that ring of the eNBs in the DVB cell. In Figures 6.11 and 6.12 we plot the LTE loading against the fractional distance of an eNB ring in the central DVB cell, for different ISDs. The smaller we

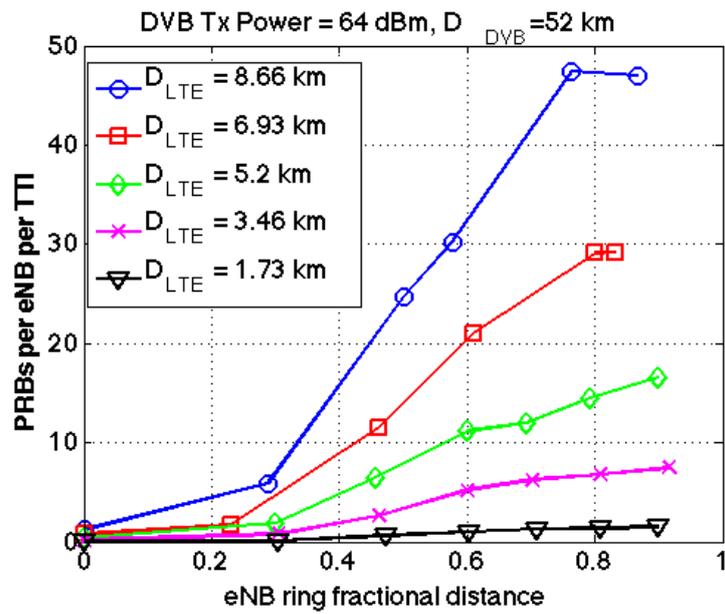


Figure 6.11: PRBs per eNB per TTI vs Fractional distance in DVB central cell, for DVB Tx Power = 64 dBm

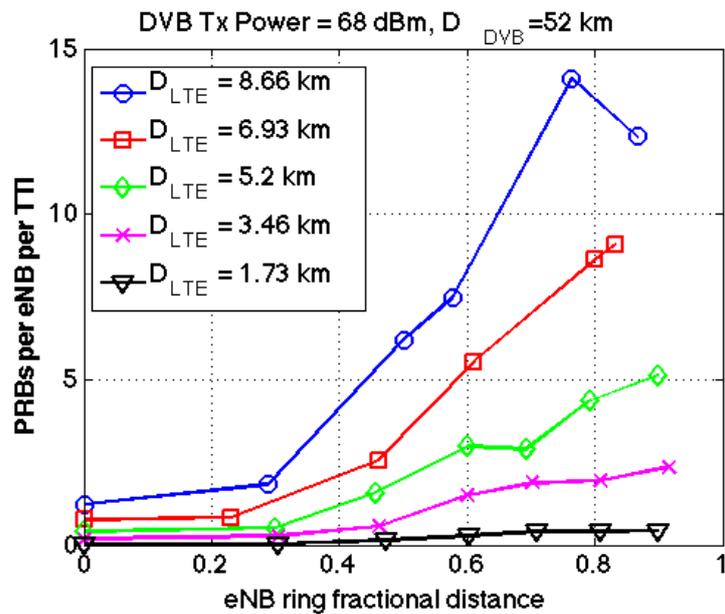


Figure 6.12: PRBs per eNB per TTI vs Fractional distance in DVB central cell, for DVB Tx Power = 68 dBm

keep the LTE ISD, the lesser the per eNB load is, because for smaller ISD we have more eNBs to share the same load in the DVB cell. In Figure 6.11 for $D_{LTE} = 8.66$ km and $P_t = 64$ dBm, the eNB on the cell edge requires almost all the available capacity, but in figure 6.12 for the same ISD, the DVB power transmission is raised by 4 dBs, it reduces per eNB load by 70%, which becomes 15 PRBs per TTI per eNB. Thus having

such a cooperation between the DVB and the LTE networks enables an efficient TV transmission by making the appropriate trade-offs among the parameters, i.e. DVB transmission power, load per eNB and ISD.

6.5 Summary

In the previous chapters we discussed about the characteristics of a multimedia broadcast network and studied the handheld coverage problems for a multimedia broadcast. In this chapter we consider a population of handheld receivers in the LTE network which could receive the DVB transmission also. We propose a simple cooperative role for the LTE network, which retransmits the lost packets from the DVB transmission to the handheld receivers. The retransmission of the lost BB-frames generates some additional load in the LTE network.

The probability of the BB-frames loss at each handheld receiver depends on the SINR of the DVB signal received at the handheld receiver. A handheld receiver receives the DVB signal at a high SINR if the DVB transmission power is high. Thus additional load in the LTE network is related to the DVB transmission power. All the handheld receivers are covered against the additional load in the LTE network due to retransmission of the lost packets. For a typical DVB transmission power level the so-generated additional load constitutes a small percentage of the LTE network capacity. Even for low DVB transmission power levels the additional load makes a reasonable percentage of the capacity for large LTE cells. By reducing the LTE cell size the additional per-eNB-load can be reduced. In our simulations we consider only macro cells, however, the gains in terms of reduced capacity reservation can even be higher for micro and femto cells. Hence, we conclude the available capacity in the LTE network to be enough for supporting the proposed retransmission of the lost BB-frames.

7.1 Summarizing the elements

In this thesis work we focused on evolving an interworking frame-work between two multimedia networks of different orientations. A cellular network has bidirectional links and the data transfers are transactional and temporary in nature. With a proper resource management a cellular network can guarantee a given QoS. On the contrary a DVB network mechanism is unidirectional and lacks the ability of ensuring a certain level of QoS. However, the typical broadcast networks i.e. DVB networks have wide coverage and high capacity.

The advancements in processing, display and circuit integration technologies paved a way to the recent arrivals of highly capable handheld multimedia devices in the market. Thus to provide a rich multimedia experience for the handheld users, robust and high capacity wireless links are required. Thus keeping in view the coming-up expectations of the mobile multimedia users, it is essential to determine the synergic gains of the futuristic inter-technological cooperations.

We propose a cooperative retransmission of the lost packets in a multimedia broadcast reception at the handheld receivers. In our proposal the cellular network is considered to support a retransmission mechanism for the lost packets from DVB transmission to the handheld receivers. Our thesis work can be classified into five functional parts:

- Analysis of service outage for the DVB transmission to the handheld receivers
- Study of the SFN characteristics of a DVB network
- Study of the DVB-T2 packet structures
- Proposal and analysis of a real-time repair of the DVB broadcast data-flow at smartphones

- Analysis of the load generated in the LTE network for retransmitting the lost DVB packets

We commenced by presenting the service outage issue for the handheld receivers in typical DVB network. Then based on our study of the DVB-T2 packet structures we consider BB-frames retransmission via LTE network. We also evaluated and analyzed the additional load generated in the LTE network in terms of the LTE resource allocation units. Another important contribution of this work is the method proposed for the identification of a BB-frame in a DVB-T2 transmission.

The core proposal of our thesis work is a repair mechanism for the high definition multimedia broadcast to the smartphones. This repair mechanism is indigenously cellular network based. In our proposal we treat the multimedia broadcast to the smartphones as a continuous data flow. The repair operation over a file-data broadcast is classically known. Our proposal introduces the concept of having real-time repair operations over a multimedia broadcast data flow, such that these operations run side by side with data flow to the smartphone.

We proposed an LTE-based Real-time Flow Repair (RFR) service for the broadcast data-flow to the smartphones. We consider a light server-client protocol for this service, namely, CoAP, which is based on user-datagrams. In order to support the proposed service a joint infra-structure is also presented. This infra-structure is enabled by having RFR servers, which inter-connect a DVB-T2 system with the LTE EPC. A RFR server has been considered on three different locations. These locations include two localized alternate locations as well, which use the offloading techniques in a cellular network i.e. SIPTO and LIPA.

7.2 Conclusive Remarks

In our thesis work we preserve the integrity of the protocol stacks of both domains i.e. DVB and LTE networks. The proposed RFR service is compliant with the routine procedures in the LTE network. In the case of regional content insertion in the DVB transmission the multimedia content originates from a local or regional venue in the DVB network, we propose the use of offloading techniques to repair a regional DVB transmission. The offloading techniques considered are SIPTO and LIPA. In both offloading techniques the LTE protocol stack is intact, as the functionality of PGW is embedded in a local Gateway in either of the two cases.

In Chapter 6 we show that the LTE network has enough capacity for supporting the additional load due to DVB packets' cooperative retransmission. Similarly, in Section 5.5, we present the values of maximum RTT delay from the literature, which are quite short w.r.t. the typical DVB packets burst interval (i.e. interleaving frame 's time duration). Thus we conclude that an LTE based real-time flow repair over the DVB-T2 transmission can be achieved. In our proposal we emphasize on having a light application protocol, therefore we base the proposed RFR service on CoAP.

7.3 Prospective Research directions

The reported thesis work has addressed the concept of DVB and LTE interworking on several aspects. There are several research directions in which the proposed work can be extended:

7.3.1 RFR service via eMBMS bearers

In the considered scenario of Chapter 6, we considered equidistant eNBs around the central DVB transmitter. Instead of retransmitting same/different BB-frames to each smartphone individually, x linear combinations of the n BB-frames per interleaving frame can be broadcasted such that those x linear combinations are enough to determine any y BB-frames lost.

Since the load over each eNB is a function of its location. Therefore all eNBs equidistant from the DVB transmitter are likely to have the same DVB retransmission load generated. Thus each eNB ring can form an SFN including the LTE cells under same level of DVB loading. One of the important bottleneck would be the performance of the concentric SFN rings in an LTE radio access network.

7.3.2 RFR service Scheduling

In our work we considered the required rate of retransmission via LTE network to be the same as the BB-frame error generation rate. There are several standard scheduling algorithms used in the LTE resource allocation, which may impact the RTT delay via LTE network. This RTT delay can affect the after-repair QoS for the broadcast data flow to the smartphones. Thus a set of amendments can be formulated for the standard scheduling algorithms.

An RFR service oriented scheduler may define several priority levels for different users seeking DVB retransmission. The scheduler controls the after-repair QoS by assigning a high or a low priority to the given DVB repair data flow via LTE network. For example, the DVB retransmission packets for the lowest level of the post-repair QoS can be at the least priority of the scheduler and vice versa.

7.3.3 RFR Bearer modification for RFR operation over regional DVB data flow

If an RFR client requests to repair a PLP carrying regional content then it has to be offloaded using SIPTO technique. Normally, SIPTO based offloading involves Mobility Management Entity (MME) in the LTE EPC. Also in the particular scenario of the RFR service, it is preferable to preserve the LTE routine procedures. Therefore the RFR server should trigger MME for the SIPTO based offloading of the RFR client from the LTE EPC. The characteristics of such an interface between the RFR server and MME are not defined. Thus it is essential to identify the additional steps invoking signal exchanges between the RFR server and MME.

7.3.4 Home-RFR server for indoor DVB handheld receivers

The fundamental aspect of this work is to ensure a good QoS for the DVB handheld receivers in any scenario. In our work we highlight about both the indoor and the outdoor scenarios. The indoor DVB handheld receivers receive weaker signals than the outdoor ones. In our RFR service proposal the closest RFR server for the clients is considered to be connected with eNBs using LIPA.

An RFR client indoors has a higher probability to be connected to the HeNB. Thus, an indoor RFR server co-located with a HeNB and a LGW can be foreseen. This study leads to the specification of a Home-RFR server. The proposed LIPA technique based Town-level RFR server required an authorization by the LTE core network. In this scenario also the UE or RFR client should be authorized like in any LIPA based data breakout in a local IP Network. Such an RFR server receives the same QEF DVB reception as the fixed receiver with roof antenna and repairs the broadcast data flow to the co-resident handheld receivers.

A

Outage probability derivation

A.1 Smeed's population density

The computational steps for the derivation of DVB service outage for the Smeed's population density are presented as following:

The outage probability as a function of the distance is given as

$$\epsilon(r) = \frac{1}{2} \left(1 - \operatorname{erf} \left(b_1(C_{plan} - C_{min}) - b_2 \ln \left(\frac{r}{R} \right) \right) \right), \quad (\text{A.1})$$

in (3.12). The form of Smeed's model considered for the derivation is given as,

$$\rho(r, \theta) = \frac{(i+2)N}{2\pi R^{i+2}} r^i, \quad (\text{A.2})$$

in (3.14). We calculate the average per-user DVB service outage by using,

$$\epsilon_s = \frac{\int \int_s \epsilon(r) \rho(r, \theta) r dr d\theta}{\int \int_s \rho(r, \theta) r dr d\theta}, \quad (\text{A.3})$$

as given in (3.13).

After putting the values from (A.1) and (A.2) into the integrals of (A.3) we get,

$$\epsilon_s = \left(\frac{\pi R^{i+2}}{i+2} + \pi \int_0^R \left[\operatorname{erf} \left(b_1(C_{min} - C_{plan}) + b_2 \ln \left(\frac{r}{R} \right) \right) \right] r^{i+1} dr \right) \frac{i+2}{2\pi R^{i+2}}. \quad (\text{A.4})$$

Let,

$$I = \int_0^R \left[\operatorname{erf} \left(b_1(C_{min} - C_{plan}) + b_2 \ln \left(\frac{r}{R} \right) \right) \right] r^{i+1} dr,$$

which can also be shown as,

$$I = \int_0^R \frac{[\text{erf}(\alpha + \beta \ln(r))] r^{i+2}}{r} dr,$$

where, $\beta = b_2$, $\alpha = b_1(C_{min} - C_{plan}) - b_2 \ln(R)$. We take $M = C_{plan} - C_{min}$, therefore, $\alpha = -b_1M - b_2 \ln(R)$.

Let $t = \alpha + \beta \ln(r)$ then, $r = e^{(t-\alpha)/\beta}$ and $\frac{dr}{r} = \frac{dt}{\beta}$. Let $t1$ be the upper limit of the integral, then for $r = R$ and $t = t1$ we can relate $t1$ with R as $t1 = \alpha + \beta \ln(R) = -b_1M$.

Thus we get,

$$I = \frac{1}{\beta} \int_{-\infty}^{t1} [\text{erf}(t)] \left(e^{\frac{t-\alpha}{\beta}} \right)^{i+2} dt,$$

which can also be given as,

$$I = \frac{e^{-\frac{\alpha(i+2)}{\beta}}}{\beta} \int_{-\infty}^{t1} [\text{erf}(t)] e^{\frac{(i+2)t}{\beta}} dt.$$

Let $\beta_1 = \frac{i+2}{\beta}$. Then integral I can be rewritten as,

$$I = \frac{\beta_1 e^{-\alpha\beta_1}}{i+2} \int_{-\infty}^{t1} [\text{erf}(t)] e^{\beta_1 t} dt.$$

Let $I_1 = \int_{-\infty}^{t1} [\text{erf}(t)] e^{\beta_1 t} dt$. Since, $\text{erf}(q) = \frac{2}{\sqrt{\pi}} \int_0^q e^{-p^2} dp$ and $\int_0^w x dy = xy|_0^w - \int_0^w y dx$.

We take $x = \text{erf}(t)$ which can be derived as, $dx = \frac{2}{\sqrt{\pi}} e^{-t^2}$. We take $dy = e^{\beta_1 t}$, therefore, $y = \frac{e^{-\beta_1 t}}{\beta_1}$. Thus, $I_1 = \text{erf}(t1) \frac{e^{\beta_1 t1}}{\beta_1} - \frac{2}{\beta_1 \sqrt{\pi}} \int_{-\infty}^{t1} e^{-t^2 + \beta_1 t} dt$.

$$I_1 = \frac{1}{\beta_1} (\text{erf}(t1) e^{\beta_1 t1}) - \frac{2e^{\frac{\beta_1^2}{4}}}{\sqrt{\pi}} \int_{-\infty}^{t1 - \frac{\beta_1}{2}} e^{-\nu^2} d\nu \quad (\text{for } \nu = t - \frac{\beta_1}{2}).$$

$$\text{We know that, } \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{u^2}{2}} du = \frac{1}{2} \left(1 + \text{erf} \left(\frac{x}{\sqrt{2}} \right) \right).$$

Let us assume $\nu = \frac{w}{\sqrt{2}}$,

$$\text{which gives, } I_1 = \frac{1}{\beta_1} \text{erf}(t1) e^{\beta_1 t1} - \frac{2e^{\frac{\beta_1^2}{4}}}{\sqrt{2\pi}} \int_{-\infty}^{\sqrt{2}(t1 - \frac{\beta_1}{2})} e^{-\frac{w^2}{2}} dw,$$

$$\text{using erf function, } I_1 = \frac{1}{\beta_1} \left(e^{\beta_1 t1} \text{erf}(t1) - e^{\frac{\beta_1}{4}} \left(1 + \text{erf} \left(t1 - \frac{\beta_1}{2} \right) \right) \right),$$

$$\text{which is, } I_1 = \frac{\beta}{i+2} \left(e^{\frac{i+2}{\beta} t1} \text{erf}(t1) - e^{\frac{(i+2)^2}{4\beta^2}} \left(1 + \text{erf} \left(t1 - \frac{i+2}{2\beta} \right) \right) \right).$$

Putting I_1 value into the integral I ,

$$I = \frac{e^{-\frac{\alpha(i+2)}{\beta}}}{i+2} \left(e^{\frac{i+2}{\beta}t1} \operatorname{erf}(t1) - e^{\frac{(i+2)^2}{4\beta^2}} \left(1 + \operatorname{erf} \left(t1 - \frac{i+2}{2\beta} \right) \right) \right).$$

By putting the values $\alpha = -b_1M - b_2 \ln(R)$, $\beta = b_2$ and $t1 = -b_1M$, the solution of integral I can be re-written as,

$$I = -\frac{R^{i+2}}{i+2} \left[\operatorname{erf}(b_1M) + e^{\frac{4b_1b_2(i+2)M+(i+2)^2}{4b_2^2}} \left(1 - \operatorname{erf} \left(b_1M + \frac{i+2}{2b_2} \right) \right) \right]. \quad (\text{A.5})$$

Putting the value of I into (A.4) gives the service outage probability for Smeed's population density as,

$$\begin{aligned} \epsilon_s &= \frac{1}{2} (1 - \operatorname{erf}(b_1M)) \\ &- \frac{1}{2} e^{\frac{(i+2)^2+4b_1b_2M(i+2)}{4b_2^2}} \left(1 - \operatorname{erf} \left(b_1M + \frac{i+2}{2b_2} \right) \right), \end{aligned} \quad (\text{A.6})$$

as presented in (3.16) also.

A.2 Clark's population density

The computational steps for the derivation of DVB service outage for the Clark's population density are presented as following:

The outage probability as a function of the distance is given as in A.1. The form of Clark's Model considered for the derivation is given as,

$$\rho(r, \theta) = \frac{Nb^2}{2\pi (1 - e^{-bR}(1 + bR))} e^{-br}, \quad (\text{A.7})$$

in (3.19). We calculate the average per-user service outage by using (A.3).

After putting the values from (A.1) and (A.7) into the integrals of (A.3) we get,

$$\epsilon_s = \frac{1}{2} + \frac{1}{2} \frac{b^2}{1 - e^{-bR}(1 + bR)} \int_0^R \operatorname{erf} \left(-b_1M + b_2 \ln \left(\frac{r}{R} \right) \right) e^{-br} r dr. \quad (\text{A.8})$$

The exponential function of (A.8) is expanded using Taylor series i.e. $e^{-br} = \sum_{j=0}^{\infty} \frac{(-br)^j}{j!}$. Thus, (A.8) can be given as,

$$\epsilon_s = \frac{1}{2} + \frac{1}{2} \frac{b^2}{1 - e^{-bR}(1 + bR)} \sum_{j=0}^{\infty} \frac{(-b)^j}{j!} \int_0^R \operatorname{erf}\left(-b_1 M + b_2 \ln\left(\frac{r}{R}\right)\right) r^{j+1} dr. \quad (\text{A.9})$$

The integral I from Section A.1 can be identified in (A.9). Thus, we put the solution for integral I from (A.5) into (A.9). Thus, the average outage probability for Clark's population density model is given as,

$$\epsilon_s = \frac{1}{2} \left(1 - A \sum_{j=0}^{\infty} B_j (\operatorname{erf}(b_1 M) + C_j) \right), \quad (\text{A.10})$$

where,

$$\begin{aligned} A &= \frac{(bR)^2}{1 - e^{-bR}(1 + bR)}, \\ B_j &= \frac{(-bR)^j}{(j+2)j!}, \\ C_j &= e^{\frac{(j+2)^2 + 4b_1 b_2 M(j+2)}{4b_2^2}} \left(1 - \operatorname{erf}\left(b_1 M + \frac{j+2}{2b_2}\right) \right). \end{aligned}$$

Moreover, A and B_j can be parametrized with $bR = \ln\left(\frac{\rho_o}{\rho_e}\right)$ as,

$$\begin{aligned} A &= \frac{\left(\ln\left(\frac{\rho_o}{\rho_e}\right)\right)^2}{1 - \frac{\rho_e}{\rho_o} \left(1 + \ln\left(\frac{\rho_o}{\rho_e}\right)\right)}, \\ B_j &= \frac{\left(\ln\left(\frac{\rho_e}{\rho_o}\right)\right)^j}{(j+2)j!}. \end{aligned}$$

B Error performance modelling

In [36] there are Bit Error Rate (BER) vs SINR simulation results for DVB-T2 in different channel conditions. Because of our emphasis on coverage for Handheld users we choose Typical Urban - 6 taps (TU-6) channel. We fit sigmoidal curves over the simulation results from [36]. Examples of sigmoidal curve-fitting can also be found in other works such as [94], [95] and [96].

Since Quasi Error Free (QEF) is almost impossible to simulate as QEF level for DVB-T2 requires $BER = 10^{-11}$. Therefore, the only solution to have error performance model till QEF level is to extrapolate the fits for $BER = 10^{-11}$ [3]. The sigmoidal curve considered for fitting is,

$$BER_{fit} = 1 - \frac{1}{1 + e^{a_1(SINR)^2 + a_2(SINR) + a_3}}, \quad (\text{B.1})$$

where BER_{fit} is the BER obtained using this model and a_1 , a_2 and a_3 are the parameters specific for a curve.

The values of a_1 , a_2 and a_3 are determined for the least sum of squared logarithmic differences between the values from the fit, BER_{fit} and the simulation values, BER_{sim} . Thus the mathematical representation of the fitting metric is given as, $fittingmetric = \sum_{i=1}^p (\log BER_{fit(i)} - \log BER_{sim(i)})^2$.

List of Publications

Peer-reviewed International Conferences

- ◇ Anis, M.M.; Lagrange, X.; Pyndiah, R., "Handheld Receivers Coverage by DVB-T2," Vehicular Technology Conference (VTC Fall), 2012 IEEE , 3-6 Sept. 2012, Quebec City, CANADA, doi: 10.1109/VTCFall.2012.6399000
- ◇ Anis, M.M.; Lagrange, X.; Pyndiah, R., "Analyzing the coverage of the Single Frequency Broadcast Network for handheld receivers," Consumer Communications and Networking Conference (CCNC), 2013 IEEE , 11-14 Jan. 2013, Las Vegas, NV, doi: 10.1109/CCNC.2013.6488527
- ◇ Anis, M.M.; Lagrange, X.; Pyndiah, R., "A simple model for DVB and LTE cooperation," International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), 2013 IEEE, 5-7 June 2013, London, United Kingdom, doi: 10.1109/BMSB.2013.6621778

In preparation

- Anis, M.M.; Lagrange, X.; Pyndiah, R., "LTE-based real-time broadcast data-flow repair at smartphones," to be submitted as a journal article, November, 2013

Bibliography

- [1] A122, *Digital Video Broadcasting (DVB); Frame structure channel coding and modulation for a second generation digital terrestrial television broadcasting system (DVB-T2)*, 2011.
- [2] M. M. Anis, X. Lagrange, and R. Pyndiah, "Handheld receivers coverage by DVB-T2," in *Vehicular Technology Conference, 2012. VTC2012-Fall. IEEE 76th*, Sep. 2012.
- [3] A133, "*Implementation guidelines for a second generation digital terrestrial television broadcasting system (DVB-T2)*", 2010.
- [4] 3GPP, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 10)," *TS 36.213 V10.2.0*, 2011.
- [5] J. S. E. Dahlman, S. Parkvall, *4G: LTE/LTE-Advanced for Mobile Broadband*. Elsevier Inc., first ed., 2011.
- [6] O. N. C. Yilmaz, "Self-Optimization of Coverage and Capacity in LTE using Adaptive Antenna Systems," *Aalto University School of Science and Technology*, vol. Master 's Thesis, 2010.
- [7] EBU UER Technical Report, *EBU - TECH 3348: Frequency and Network Planning aspects of DVB-T2*, 2011.
- [8] J.-A. Ibanez, T. Lohmar, D. Turina, and A. Zanin, "Mobile TV over 3G networks: Service and enablers evolution," *Ericson, White paper*, 2008.
- [9] A. Kumar, *Implementing Mobile TV*. Elsevier Inc., second ed., 2010.
- [10] CISCO, "Cisco Visual Networking Index: Forecast and Methodology, 2012-2017," *White paper*, 2013.

- [11] D. Turina and T. Lohmar, "Mobile tv - the concept overview and technology enablers," in *Telecommunications, 2007. ConTel 2007. 9th International Conference on*, pp. 345–345, 2007.
- [12] J. T. J. Penttinen, P. Jolma, E. Aaltonen, and J. Vare, *The DVB-H handbook: The Functioning and Planning of Mobile TV*. John Wiley and Sons, Ltd, Publication, first ed., 2009.
- [13] Digital Video Broadcasting (DVB), "A Cooperation between 3GPP and the DVB Project on a common downlink only standard?," in *Co-operation between 3GPP and the DVB Project*, (Kansas City, USA), March 2011.
- [14] G. Faria, J. A. Henriksson, E. Stare, and P. Talmola, "DVB-H: Digital Broadcast services to handheld devices," *IEEE Proceedings of January, Invited Paper*, vol. 94, 2006.
- [15] A160, *Digital Video Broadcasting (DVB); Next Generation broadcasting system to Handheld, physical layer specification (DVB-NGH)*, November 2012.
- [16] 3GPP, "Technical Specification Group Services and System Aspects; Multimedia Broadcast/Multicast Service (MBMS); Architecture and functional description (Release 9)," *TS 23.246 V9.5.0*, 2010.
- [17] Z. Niu, L. Long, J. Song, and C. Pan, "A new paradigm for mobile multimedia broadcasting based on integrated communication and broadcast networks," *Communications Magazine, IEEE*, vol. 46, no. 7, pp. 126–132, 2008.
- [18] L'Agence Nationale de la Recherche (ANR), *D21.1 - Analysis on 3GPP E-MBMS/DVB-NGH Physical layer convergence*, 2011.
- [19] L'Agence Nationale de la Recherche (ANR), *D21.2 - Analysis on 3GPP E-MBMS/DVB-NGH Physical layer convergence*, 2012.
- [20] T. Jokela, C. Hollanti, J. Lahtonen, R. Vehkalahti, and J. Paavola, "Performance evaluation of 4x2 mimo schemes for mobile broadcasting," in *Broadband Multimedia Systems and Broadcasting (BMSB), 2011 IEEE International Symposium on*, pp. 1–6, june 2011.
- [21] W. Fischer, *Digital Video and Audio Broadcasting Technology: A Practical Engineering Guide*. Springer, third ed., 2010.
- [22] DVB, *Fact sheet: Introduction to the DVB Project: Creating Global Standards for Digital Television*, 2011.

- [23] DVB-T2 Fact Sheet, *2nd Generation Terrestrial: The World 's Most Advanced Digital Terrestrial TV System*, 2011.
- [24] R. G. Gallager and P. Elias, "Low-Density Parity-Check Codes," *doctoral dissertation Electronics Research Laboratory, Massachusetts Institute of Technology*, 1960.
- [25] T. Summers, "LDPC: Another Key Step Toward Shannon," *designlines: WIRELESS and NETWORKING, EE Times University*, 2004.
- [26] ETSI, "*EN 302 755: Frame structure channel coding and modulation for a second generation digital terrestrial television broadcasting system*", v1.3.1 ed., 2012.
- [27] ENENSYS Technologies, *BENEFITS OF USING MULTIPLE PLP IN DVB-T2*, www.enesys.com/technologies ed., 2011.
- [28] M. Tormos, C. Tanougast, A. Dandache, M. Tormos, P. Bretillon, and P. Kasser, "Experimental performance of mobile DVB-T2 in SFN and distributed MISO network," in *Telecommunications (ICT), 2012 19th International Conference on*, pp. 1–5, april 2012.
- [29] L. Rong, O. Ben Haddada, and S.-E. Elayoubi, "Analytical analysis of the coverage of a mbsfn ofdma network," in *Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE*, pp. 1–5, 30 2008-dec. 4 2008.
- [30] A. Dumeur, P. Godlewski, P. Martins, and P. Debreux, "On the performance of dvb-t networks for indoor and mobile reception," in *Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th*, vol. 5, pp. 3075–3079 Vol. 5, sept. 2004.
- [31] G. Branko and S. G. C., *Tilings and Patterns*. W. H. Freeman, Newyork, 1987.
- [32] G. Pousset, Y. LOSTANLEN, and Y. CORRE, "Mobile TV Standards: DVB-T vs DVB-H," *EBU technical Reveiw*, 2008.
- [33] D. Gomez-Barquero, J. Poikonen, J. Paavola, and N. Cardona, "Development and applications of a dynamic dvb-h system-level simulator," *Broadcasting, IEEE Transactions on*, vol. 56, pp. 358–368, sept. 2010.
- [34] R. Fraile, J. F. Monserrat, G. Javier, and N. Cardona, "Letter wireless systems: Mobile radio bi-dimensional large-scale fading modelling with site-to-site cross correlation," *European Transactions on Telecommunications, Wiley InterScience*, vol. 19, pp. 101–106, February 2007.

- [35] Towercast Ltd., “<http://www.towercast.fr/>,” July 2012.
- [36] T. Jokela, M. Tupala, and J. Paavola, “Analysis of Physical Layer Signaling Transmission in DVB-T2 Systems,” *IEEE TRANSACTIONS ON BROADCASTING*, vol. 56, pp. 410–417, 2010.
- [37] L. Ardito and C. Sattler, “Mobile Broadcast Bearer technologies: A comparison,” *bmcforum*, 2009.
- [38] L. Ardito and C. Sattler, “Digital Video Broadcasting (DVB); DVB-H Implementation Guidelines,” *ETSI TR 102 377*, vol. June, 2009.
- [39] D. Gomez-barquero and A. Bria, “Feasibility of DVB-H deployment on existing wireless infrastructure,” *Proc. IWCT*, vol. Citeseer, 2005.
- [40] G. Faria, “DVB-H: To deliver Digital TV to Handheld terminals,” *Embedded Systems Conference - 3G Cellular System Design Seminar*, vol. Teamcast, 2005.
- [41] J. Gledhill, P. MacAvock, and R. Miles, *DVB-T: Hierarchical Modulation (Fact Sheet)*, wp-01 ed., 2000.
- [42] W. Fischer, *Digital Video and Audio Broadcasting Technology: A Practical Engineering Guide*. Springer, second ed., 2008.
- [43] T. Kratochvil and R. Stukavec, “Hierarchical modulation in dvb-t/h mobile tv transmission over fading channels,” in *Information Theory and Its Applications, 2008. ISITA 2008. International Symposium on*, pp. 1–6, 2008.
- [44] A. Bria and D. Gomez-Barquero, “Scalability of dvb-h deployment on existing wireless infrastructure,” in *Personal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005. IEEE 16th International Symposium on*, vol. 2, pp. 716–720 Vol. 2, 2005.
- [45] J. Lopez, D. Gomez-Barquero, C. Garcia, and N. Cardona, “Planning a mobile dvb-t network for colombia,” in *Communications, 2009. LATINCOM '09. IEEE Latin-American Conference on*, pp. 1–6, 2009.
- [46] M. Tormos, C. Tanougast, A. Dandache, P. Bretillon, and P. Kasser, “Experimental performance of mobile dvb-t2 in sfn and distributed miso network,” in *Telecommunications (ICT), 2012 19th International Conference on*, pp. 1–5, 2012.

- [47] L. Kondrad, I. Bouazizi, and M. Gabbouj, "Optimizing the dvb-t2 system for mobile broadcast," in *Broadband Multimedia Systems and Broadcasting (BMSB), 2010 IEEE International Symposium on*, pp. 1–5, 2010.
- [48] T. Kratochvil and L. Polak, "Comparison of dvb-t/h and dvb-t2 in mobile, portable and fixed tv channels," in *Telecommunications Forum (TELFOR), 2011 19th*, pp. 591–594, 2011.
- [49] TeamCast, "DVB-T2: Coming Next 3D Television over DVB-T2," 2010.
- [50] G. Berjon-Eriz, I. Eizmendi, M. Velez, G. Prieto, S. Correia, A. Arrinda, and P. Angueira, "Laboratory tests for testing dvb-t2 mobile performance," in *Broadband Multimedia Systems and Broadcasting (BMSB), 2010 IEEE International Symposium on*, pp. 1–5, 2010.
- [51] Digital Video Broadcasting (DVB), *TM 4026r1: TM-H NGH Study mission report*, 2008.
- [52] W. C. Jakes, *Microwave Mobile Communications*. IEEE Communication society, 1974.
- [53] R. J. Smeed, "The effect of kinds of routing systems on the amount of traffic in the central areas of towns," *Journal of the Institution of Highway Engineers*, vol. 10, pp. 5–26, 1963.
- [54] C. Clark, "Urban Population Densities," *Journal of the IRoyal Society*, vol. 114, pp. 490–496, 1951.
- [55] M. Sharif, R. Ghazizadeh, and P. Fan, "Spatial Dynamic Spectrum Allocation and Population Density," *Wireless Communications, Networking and Mobile Computing (WiCom)*, 2007.
- [56] Digital Video Broadcasting, *Technical Specification; Generic Stream Encapsulation (GSE) fact sheet*, 2011.
- [57] Digital Video Broadcasting, *Technical Specification; Generic Stream Encapsulation (GSE) Protocol*, v1.1.1 ed., 2007.
- [58] ENENSYS Technologies, *General Overview of DVB T2 Standard: DVB T2 Frame Structure*, www.enesys.com/technologies ed., 2011.
- [59] N. Wells, "DVB-T2 in relation to the DVB-x2 Family of Standards," *Advanced Television Systems Committee (ATSC) Inc.*, 2009.

- [60] ENENSYS Technologies, *General overview of DVB-T2 Lite*, www.enensys.com ed., 2012.
- [61] DVB Services, “<http://www.dvbservices.com/identifiers/>,” Jan. 2013.
- [62] Technical Specification, *ETSI TS 101 162 Digital Video Broadcasting (DVB); Allocation of identifiers and codes for Digital Video Broadcasting (DVB) Systems*, v1.4.1 ed., 2011.
- [63] E. Standard, *ETSI EN 300 468 Digital Video Broadcasting (DVB); Specification for Service Information (SI) in Digital Video Broadcasting (DVB) Systems*, v1.12.1 ed., 2011.
- [64] M. Makni, J. Robert, and E. Stare, “Performance analysis of time frequency slicing,” in *Electronic Media Technology (CEMT), 2011 14th ITG Conference on*, pp. 1–6, 2011.
- [65] B. Hechenleitner, “Repair costs of the ipdc/dvb-h file repair mechanism,” in *Wireless Telecommunications Symposium, 2008. WTS 2008*, pp. 137–144, 2008.
- [66] M. M. Anis, X. Lagrange, and R. Pyndiah, “Analyzing the coverage of the single frequency broadcast network for handheld receivers,” in *Consumer Communications and Networking Conference, 2013. CCNC 2013. IEEE 10th*, Jan. 2013.
- [67] Internet Engineering Task Force (IETF) RFC 6726, *FLUTE - File Delivery over Unidirectional Transport*, November 2012.
- [68] T. Paila, “Unidirectional ip-based mass file delivery protocol,” in *Wireless Communication Systems, 2004, 1st International Symposium on*, pp. 235–239, 2004.
- [69] X. Liu, S. Raza, C.-N. Chuah, and G. Cheung, “Network coding based cooperative peer-to-peer repair in wireless ad-hoc networks,” in *Communications, 2008. ICC '08. IEEE International Conference on*, pp. 2153–2158, 2008.
- [70] S. Raza, G. Cheung, and C.-N. Chuah, “Dicor: Distributed cooperative repair of multimedia broadcast losses,” in *Broadband Communications, Networks and Systems, 2008. BROADNETS 2008. 5th International Conference on*, pp. 315–322, 2008.
- [71] F. Hu and N. Sharma, “The quantitative analysis of tcp congestion control algorithm in third-generation cellular networks based on fsmc loss model and its

- performance enhancement,” in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 1, pp. 407–416 vol.1, 2002.
- [72] M. Nashiry, M. Abdullah-Al-Mahmud, M. Rahman, and M. Anjum, “Evaluation of tcp performance over mobile ip wired-cum-wireless networks,” in *Computer and Information Technology, 2008. ICCIT 2008. 11th International Conference on*, pp. 150–155, 2008.
- [73] F. Ren and C. Lin, “Modeling and improving tcp performance over cellular link with variable bandwidth,” *Mobile Computing, IEEE Transactions on*, vol. 10, no. 8, pp. 1057–1070, 2011.
- [74] C. Bormann, A. Castellani, and Z. Shelby, “Coap: An application protocol for billions of tiny internet nodes,” *Internet Computing, IEEE*, vol. 16, no. 2, pp. 62–67, 2012.
- [75] O. Bergmann, K. Hillmann, and S. Gerdes, “A coap-gateway for smart homes,” in *Computing, Networking and Communications (ICNC), 2012 International Conference on*, pp. 446–450, 2012.
- [76] D. Boswarthick, O. Elloumi, and O. Hersent, *M2M Communications: A Systems Approach*. John Wiley and Sons, Ltd, Publication, first ed., 2012.
- [77] Z. Shelby, K. Hartke, C. Borman, and B. Frank, *Constrained Application Protocol (CoAP)*, core working group internet draft ed., December 2012.
- [78] L. Zhang, T. Okamawari, and T. Fujii, “Performance evaluation of end-to-end communication quality of lte,” in *Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th*, pp. 1–5, 2012.
- [79] O. Delgado and B. Jaumard, “Scheduling and resource allocation in lte uplink with a delay requirement,” in *Communication Networks and Services Research Conference (CNSR), 2010 Eighth Annual*, pp. 268–275, 2010.
- [80] 3GPP, “Technical Specification Group Services and System Aspects; General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (Release 10),” *TS 23.401 V10.4.0*, 2011.
- [81] 3GPP, “LTE Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) (LTE-Advanced) (Release 10),” *TR 36.913 V10.0.0*, 2011.

- [82] 3GPP, “Technical Specification Group Services and System Aspects; Vocabulary for 3GPP Specifications (Release 10),” *TR 21.905 V10.0.0*, 2010.
- [83] G. M. Frederic Firmin, “The evolved packet core,” Jan. 2013.
- [84] 3GPP, “Universal Mobile Telecommunications System (UMTS); LTE; Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3 Release 11,” *TS 24.301 V11.4.0*, 2012.
- [85] 3GPP, “Digital cellular telecommunications system (Phase 2+); Universal Mobile Telecommunications System (UMTS); LTE; Mobile radio interface signalling layer 3; General Aspects, Release 10,” *TS 24.007 V10.0.0*, 2011.
- [86] 3GPP, “Technical Specification Digital cellular telecommunications system (Phase 2+); Universal Mobile Telecommunications System (UMTS); LTE; Policy and charging control architecture,” *TS 23.203 V10.6.0*, 2012.
- [87] 3GPP, “Technical Specification Group Services and System Aspects; Local IP Access and Selected IP Traffic Offload (LIPA-SIPTO)(Release 10),” *TR 23.829 V10.0.1*, 2011.
- [88] K. Samdanis, T. Taleb, and S. Schmid, “Traffic offload enhancements for eutran,” *Communications Surveys Tutorials, IEEE*, vol. 14, no. 3, pp. 884–896, 2012.
- [89] LS TELCOM, “Planning DVBT2: Advance and Challenge,” *White paper WHP01 3*, 2010.
- [90] J. Laiho, A. Wacker, and T. Novosad, *Radio Network Planning and Optimization for UMTS*. John Wiley & Sons Ltd., second ed., 2006.
- [91] C. Desset, B. Macq, and L. Vandendorpe, “Computing the word-, symbol-, and bit-error rates for block error-correcting codes,” *Communications, IEEE Transactions on*, vol. 52, pp. 910 – 921, june 2004.
- [92] A. Abdel-Razzac, S. Elayoubi, T. Chahed, and B. El Hassan, “Impact of lte and dvb-ngh cooperation on qos of mobile tv users,” in *International Conference on Communications 2013 (ICC 2013)*, pp. 1–5, 2013.
- [93] P. Mogensen, W. Na, I. Kovacs, F. Frederiksen, A. Pokhariyal, K. Pedersen, T. Kolding, K. Hugl, and M. Kuusela, “LTE Capacity Compared to the Shannon Bound,” in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, pp. 1234 –1238, april 2007.

-
- [94] S. Lembo, K. Ruttik, and O. Tirkkonen, "Modelling of convolutional code performance," *WPMC Symposium, IEEE*, vol. 11, 2008.
- [95] S. Lembo, K. Ruttik, and O. Tirkkonen, "Modelling BLER performance of puncture turbo codes," *WPMC Symposium, IEEE*, 2009.
- [96] M. M. Anis, H.-L. Maattanen, and O. Tirkkonen, "Performance prediction of a Turbo-coded link in fading channels," *Department of Communications and Networking, Aalto University School of Science and Technology*, 2010.

