



# Cooperation between LTE and emergent DVB technologies for an efficient delivery of mobile TV

Amal Abdel-Razzac

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## **Cooperation between LTE and emergent DVB technologies for an efficient delivery of mobile TV**

*presented by Amal ABDEL RAZZAC*

*defended on January 14, 2015 in front of the committee composed of*

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# THÈSE EN COTUTELLE

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École Doctorale des Sciences et Technologie (Liban)

## **Coopération entre LTE et DVB pour une solution de TV mobile optimisée**

*présentée par Amal ABDEL RAZZAC*

*soutenue le 14 Janvier, 2015 devant le jury composé de:*

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# Abstract

The broadcast/cellular cooperation for a common delivery of Mobile TV is at the heart of the emerging mobile broadcast technologies, namely the mobile extension of the second generation digital video broadcasting for terrestrial reception (DVB-T2 Lite) and its follower DVB-Next Generation Handheld (DVB-NGH). These broadcast technologies aim to cooperate with the Long Term Evolution (LTE), as the latter is intended to be the bearer of Mobile TV thanks to its enhanced-Multimedia Broadcast and Multicast Service feature (e-MBMS).

Even though the 3GPP/DVB cooperation is not a new topic and was investigated with the introduction of the previous DVB technology, known as DVB-Handheld (DVB-H), most of the works addressing this issue considered a common service area covered by both DVB and cellular systems and focused solely on the impact of such cooperation in terms of capacity gains brought by 3GPP and error repair gains brought by DVB. This strategy was judged to be expensive since a new and very dense DVB network was needed. In order to overcome this problem and decrease as much as possible the need for a new broadcast network, we propose in this thesis a hybrid DVB/LTE network with a coverage extension strategy, where the LTE system, planned for almost a universal coverage, is used to deliver Mobile TV in areas not covered by recent DVB-T2 Lite (or eventually DVB-NGH) network. In this context, we explore two main issues:

1. Mobile TV services have to share LTE resources with other higher priority services such as voice traffic. The dynamicity of the latter will impact the Quality of Service (QoS) of Mobile TV. We propose a new QoS-based planning for the hybrid DVB/LTE so as to guarantee an acceptable watching experience without over-dimensioning the LTE system. We derive using Markov chain analysis and hitting time theory, several QoS metrics pertaining to mobile TV performance, such as interruption frequency and duration.
2. A new business model which clarifies the relationships between the different actors of the ecosystem namely DVB and LTE operators as well as the TV

channel providers and constructs the service area from an economic point of view is needed. In fact, the absence of a clear and viable economic model that resolves the monetary conflicts between cellular and broadcast operators was one of the main drawbacks behind the failure of the first attempt of mobile TV delivery by cooperating UMTS/DVB-H. We develop in this thesis a profit sharing strategy for the cooperative network, using coalition game concept Shapley value and Nash equilibrium for a self-enforcing strategy. We further develop a new framework using real option theory coupled with coalition games for investment decision in mobile TV networks (whether an operator should enter the mobile TV market and, if yes, when to do so) and show how operators can incorporate the uncertainties related to demand and network operation costs. We propose a bi-level dynamic programming algorithm to solve numerically the developed real option game.

**Keywords:***DVB-T2 Lite, DVB-NGH, LTE, Cooperation, QoS, Markov theory, Shapley Value, Game theory, Real option theory, Bi-level dynamic programming.*

# Résumé

La coopération entre les réseaux de diffusion classiques et les réseaux mobiles cellulaires pour une distribution commune de la télévision mobile est actuellement l'un des éléments clés discutés dans le cadre des nouvelles technologies de diffusion mobile; surtout l'extension mobile de la deuxième génération de diffusion de la télévision numérique terrestre (DVB-T2 Lite) et son suiveur le DVB-Next Generation Handheld (DVB-NGH).

En fait, ces technologies de diffusion visent à coopérer avec la récente technologie de téléphonie mobile, connue sous le nom de Long Term Evolution (LTE) qui permet la diffusion de la TV Mobile grâce au protocole de diffusion des services multimédia dans les réseaux de téléphonie mobile (de nature unicast à priori) et connu sous le nom de enhanced-Multimedia Broadcast and Multicast Service feature (e-MBMS).

Bien que la coopération entre les réseaux de diffusion DVB et ceux de téléphonie mobile n'est pas un nouveau sujet et a été étudiée avec l'introduction de la technologie de diffusion mobile précédente, connue sous le nom DVB-Handheld (DVB-H), la plupart des travaux traitants ce sujet ont considéré un scénario avec une zone de couverture commune entre le réseau de diffusion et celui cellulaire et ont évalué cette coopération en terme des gains de capacité apportés par DVB au réseau cellulaire et en terme d'amélioration de la fiabilité de transmission apportée par les réseaux cellulaire au DVB grâce à la possibilité des retransmissions unicast.

Ce scénario a été jugé comme étant coûteux vue qu'un dense réseau DVB a été nécessaire. Nous proposons, alors, dans cette thèse un réseau coopérative où coexistent l'opérateur LTE et celui DVB-T2 Lite (ou éventuellement DVB-NGH) dans un scénario d'extension de la couverture. En d'autre terme, afin de réduire autant que possible le besoin d'ajout d'un nouveau réseau de diffusion on propose d'utiliser le système LTE, planifié pour assurer une couverture presque universelle pour fournir la télévision mobile dans les zones non couvertes par DVB déjà implémenté. Nous considérons, dans ce contexte, deux points principaux:

1. Les services de la TV mobile doivent partager les ressources fréquentielles du LTE avec les autres services tels que le trafic voix. Le caractère dynamique de



ce dernier a un impact sur la qualité de service (QoS) de la télévision mobile; en d'autres termes, le trafic voix étant plus prioritaire peut, dans certaines périodes de temps, consommer toutes les ressources fréquentielles et le LTE ne peut plus servir la TV Mobile. Nous proposons, alors, une nouvelle stratégie de planification du réseau coopérative DVB/LTE qui garantit une certaine qualité de service sans sur-dimensionner le système LTE. Nous explorons, dans ce but, l'évolution des chaînes de Markov et la théorie des temps de passage et nous dérivons plusieurs indicateurs de qualité de service relatives à la performance de la télévision mobile, tels que la fréquence et la durée d'interruption de service.

2. Un nouveau modèle économique qui clarifie les relations entre les différents acteurs de l'écosystème (DVB, LTE et les fournisseurs des canaux TV) s'est avéré nécessaire dans ce type de réseaux coopératifs. En fait, l'absence d'un modèle économique clair et viable qui résout les conflits monétaires entre les opérateurs de téléphonie mobile et ceux de diffusion a été l'un des principaux causes aboutissant à l'échec de la première tentative de diffusion de la télévision mobile dans le réseau coopératif de UMTS et DVB-H. Nous développons, alors, dans cette thèse une stratégie de distribution des profits entre les contributeurs dans ce réseau coopératif. Nous exploitons la notion de la valeur de Shapley et la théorie de jeu; surtout l'équilibre de Nash pour aboutir à la partition optimale et équitable des gains. Nous investiguons également la décision d'investissement dans les réseaux de télévision mobile (si un opérateur doit entrer sur le marché de la télévision mobile et, si oui, quand le faire). Nous exploitons la théorie des options réelles couplée avec la théorie de jeu et nous montrons comment les opérateurs peuvent intégrer les incertitudes liées à la demande et aux coûts de l'opération du réseau dans leurs décisions. Nous proposons un algorithme de programmation dynamique à deux niveaux pour résoudre numériquement le problème formulé.

**Mots clés:** *DVB-T2 Lite, DVB-NGH, LTE, Coopération, QoS, Théorie de Markov, Valeur Shapley, Théorie de jeu, Théorie des options réelles, Programmation dynamique*

*To my parents, my sister and brothers  
Thank you for all of your support along the way*



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*He who does not thank people does  
not thank God*

---

*Prophet Muhammad*

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# List of Abbreviations

3GPP	Third Generation Project Partnership
AL FEC	Application Layer Forward Error Correction
AMC	Adaptive Modulation and Coding
BER	Bit Error Rate
C/N	Carrier to Noise ratio
CBR	Constant Bit Rate
CR	Code Rate
CTMC	Continuous Time Markov Chain
Discount Cash Flow	DCF
DTMC	Discrete Time Markov Chain
DTT	Digital Terrestrial Television
DVB-H	Digital Video Broadcasting handheld
DVB-NGH	Digital Video Broadcasting Next generation handheld
DVB-T	Digital Video Broadcasting - Terrestrial
DVB-T2	Digital Video Broadcasting Second Generation Terrestrial
DVB-T2 Lite	Mobile extension of DVB-T2
EBU	European Broadcastion Union
e-MBMS	Enhanced Multimedia Broadcast and Multicast Service
eNB	E-UTRAN Node B
FEC	Forward Error Correction
FEF	Future Extension Frame
FER	Frame Error Rate
FFT	Fast Fourier Transform
GBM	Geometric Brownian Motion
Geometric O-U	Geometric Ornstein-Uhlenbeck
GI	Guard Interval
HARQ	Hybrid Automatic repeat request
HD	High Definition
HP	High Priority
ISD	Inter Site Distance
LP	Low Priority
LTE	Long Term Evolution
Marginal Contribution	MC
MBMS	Multimedia Broadcast and Multicast Service

MCS	Modulation and Code rate Scheme
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
MOD	Modulation
MPE-FEC	Multi Protocol Encapsulated Forward Error Correction
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDU	Protocol Data Units
PLP	Physical Layer Pipe
PRB	Physical Resource Block
PS	Processor Sharing
QAM	Quadrature amplitude modulation
QoS	Quality Of Service
QPSK	Quadrature phase-shift keying
SB	Source Blocks
SC-FDMA	Single Carrier Frequency Division Multiple Access
SD	Single Definition
SFN	Single Frequency Netwok
SINR	Signal-to-interference Noise Ratio
SISO	Single Input Single Output
SVC	Scalable Video Coding
TDM	Time Division Multiplexing
UMTS	Universal Mobile Telecommunications System
VBR	Variable Bit Rate

# Chapter 1

## Introduction

### 1.1 Mobile TV trends

The perpetual development of wireless communication technologies is changing our daily life. We are, no doubt, witnessing the era of “Anytime, Anywhere, Anything” communication. We, all, search to be free, mobile and connected. The popularity of sophisticated terminals and smartphones is indeed accelerating this fact and creating new applications demands.

Live Mobile TV is one of the most representative services of these new demands. This fact is attested by many recent surveys. For example, in a recent survey of UK mobile subscribers between the ages of 18-44 [2], 63% reported watching video on a smartphone or tablet compared to 51% last year. 50% prefer Live programs while 40% are more into video on demand. 37% of consumers watch Mobile TV at home while 25% access Mobile TV between activities (while waiting for an appointment, at work, etc) and 20% use this application on the move. In another survey in US [3], 35% of the respondents indicate that they have tried mobile TV and/or video services and 27% are current users of this service. Another 26% of the respondents have not tried the service because it is not available from their TV or mobile service provider. Once again, Live programs is the most preferred Mobile TV service for 51% of the respondents and video on demand for 34% of them. In US also, the home is the place where the majority of the users prefer to watch mobile TV, and this is reported by 47% of the current users while 13% use it in-between activities, 10% at work and 8% while in transit.

So, Mobile TV has nowadays become a reality and users are more into watching Live contents on handheld devices. The surprising fact revealed by surveys is that



users mostly watch Mobile TV at home with extended watching hours. As a matter of fact, telecommunication and Digital Video Broadcasting (DVB) operators targeting this new integrated service should be prepared to deliver a good quality of live videos especially for indoor users, because the success of Mobile TV as well as any consumer business is tightly related to the user's needs, motivations and most importantly their watching experience satisfaction.

## 1.2 Delivery solutions and operators readiness

The 3<sup>rd</sup> Generation Partnership Project(3GPP) telecommunications networks are typically well dimensioned to reach indoor users. Furthermore, the huge widespread of sophisticated teleco-devices among users promises a fast roll-out of Mobile TV over existent infrastructure. However, the main issue that prevents these operators from offering rich Mobile TV services remains the lack of bandwidth for such greedy applications. Many improvements were done by 3GPP to cope with the high demand on bandwidth and were introduced in the Long Term Evolution (LTE) standard [4], which is intended to be the bearer of Mobile TV, but the limited bandwidth problem still exists, especially that mobile multimedia traffic will increase dramatically over the upcoming years [5] and has thus to share the bandwidth with mobile basic traffic, namely voice and data traffic.

On the other hand, DVB operators, with their high bandwidth resources, have always been the best candidate for offering TV and radio broadcast services. But these parties targeted mostly fixed reception. The mobile broadcast, introduced primarily with DVB-Handheld (DVB-H) [6], which is the extension of the DVB-Terrestrial (DVB-T) [7], failed dramatically mainly because of the lack of friendly, low price, handheld devices as well as the expensive additional infrastructure needed to serve nomadic users, especially indoor ones.

3GPP and DVB organizations realized their complementarity and the benefits they could bring to each other. They started to consider cooperation for an efficient Mobile TV delivery. The chairman of the DVB project revealed, in its presentation in a 3GPP-DVB joint workshop for next generation Mobile TV standards [1], that they are interested in this cooperation and they believe that it will be a win-win solution for both 3GPP and DVB projects and satisfy the end user as well: DVB is a leader in the area of broadcast solutions and can help, thus, 3GPP. The latter, however, has a big subscriber base and well integrated devices and can solve, thus, the screening problem which encountered the very first attempt with DVB-H. Finally, the DVB parties think that a cooperative overlay network can balance the Mobile TV load

between both networks and give, thus, a lower cost national Mobile TV coverage and users will be connected wherever they are.

This cooperation is foreseen to be possible in the context of LTE and new DVB standards targeting handheld reception, namely DVB-T2 Lite (Annex I [8]), the mobile extension of DVB-T2 [8][9], which is itself an improvement to DVB-T, and its potential follower DVB-NGH [10].

Those organizations did think about cooperation earlier with their old technologies: 3GPP Universal Mobile Telecommunications System (UMTS) and DVB-H. But the market was not ready to consider video services, User Equipments (UE) were not as developed and many technological and monetary conflicts prevented their cooperation [1].

## 1.3 Contributions of the thesis

We consider in this thesis a hybrid network where both LTE and emerging mobile DVB infrastructures coexist, and study their cooperation to offer a seamless Mobile TV service, keeping in mind the UMTS/DVB-H experience. This thesis contributions fall into two parts: a technological part concerned mainly with dimensioning issues and an economical part focusing mainly on profit sharing between the different actors of the system.

### 1. Part I: Planning and dimensioning of the cooperative network

This part focuses on the planning of the LTE/DVB cooperative network. We consider a coverage extension scenario where the mobile TV service area is divided into areas where users are served by DVB-T2 Lite (or DVB-NGH) and other areas where the service is delivered by the LTE bearer. The main problem in such a hybrid network is the performance of mobile TV in the LTE network. A simple solution is to dedicate a given LTE bandwidth for Mobile TV services. However, this approach is rather expensive in terms of the needed LTE bandwidth. We hence propose a realistic, more practical and less expensive solution, where the Mobile TV services share dynamically the LTE resources with other real-time unicast services (i.e. voice calls) and best effort ones (i.e. data). Even though Mobile TV services, which have lower priority than voice calls, might not be always delivered due to lack of bandwidth, this solution owes its feasibility to the fact that user perception of video can cope with some interruptions in the service delivery, which enables new dimensioning based on so-called user Quality of Service (QoS). we make two contributions in this context:

- **Derivation of QoS metrics to describe Mobile TV performance:** We derive, using Markov chain analysis and hitting time theory, several QoS metrics pertaining to mobile TV performance, such as the frequency and duration of service interruption.
- **Impact of the introduction of a buffer at the receiver side:** We extend the previous model by considering a playout buffer at the receiver side so as to enhance the performance in cases of service interruption. We propose a buffering model pertaining the live nature of TV service and develop the corresponding markov chain study.

## 2. Part II: Definition of a business model for the cooperative network:

The economical issue is another fundamental subject to consider while evaluating the LTE/DVB cooperative strategy. In fact, the success of any service is tightly related to its affordability. The latter is influenced by many parameters, such as the user equipments price and the subscription fees which are in turn the results of operators target profits given their infrastructures costs.

The monetary matter is more complicated in hybrid networks, where selfish behaviours of the leader agents (the operators in our case) can prevent their cooperation. The absence of a clear and viable economical model that resolves the monetary conflicts between cellular and broadcast operators was however one of the main drawbacks behind the failure of the first attempt to deliver mobile TV service by cooperating UMTS/DVB-H: “*The first refused to fund a new network (and thus new antennas), the second, paralyzed by the collapse of the advertising market, also refused to spend a penny*” as put by the author in [11].

We hence propose a new business model that helps overcome these behaviours towards a fair, self-enforcing agreement guaranteeing each party’s share of profit. We make use of two analytical tools:

- **Shapley value for a fair profit distribution:** It is an interesting solution, defined by Lloyd Shapley, to distribute pay-offs/gains of cooperative as well as bargaining games [12]. We use its properties and axioms to develop closed form equations defining the profit share of each player in the Mobile TV value chain according to its contribution to the service delivery. We prove also, that under this distribution, both LTE and DVB operators, targeting the same mobile TV service, will have the incentive to cooperate to earn more profits without increasing the service subscription fees, and they will have the same optimal network configuration (optimal partition

of service region between LTE and DVB and optimal number of served TV channels).

This study is combined with a game theoretical Nash Equilibrium [13]. In fact, the operators are not the only agents that aspire to make profits, there are also the TV channel providers. We, however, prove that the latter, unlike the operators, will not always have the incentive to cooperate and may leave the Mobile TV delivery coalition. The withdrawal of these players after the network configuration and the launch of the service will upset the operators and lead to unexpected losses. And, so, even though we have a cooperative game, there is a competition between the possible coalitions (and not the players themselves) and it is important to determine from the very beginning which network configuration is stable as well as the set of TV channels to be delivered. This is achieved by the Nash equilibrium.

- **Real option theory for an optimal investment timing:** We address, further, the question of whether an operator should enter the mobile TV market and, if yes, when to do so, based on the expected variation of the market state. We consider two main sources of uncertainty: user demand and network operation cost and propose a strategic investment framework for mobile TV infrastructure based on a dynamic game theoretical framework combining real option theory with coalition games.

## 1.4 Organization of the thesis

The remainder of this document is organized as follows:

In Chapter 2, we give a brief overview of the 3GPP and DVB solutions for Mobile TV delivery. We focus especially on the new emerging solutions, and the considered one in this thesis, the LTE and the next DVB handhld technology DVB-T2-Lite and eventually DVB-NGH. We propose an implementation of a LTE/DVB cooperative network for an efficient delivery of Mobile TV and dimension it taking into account infrastructural and QoS issues. We investigate, further, the impact of playout buffer on the service quality in Chapter 3.

In Chapter 4, we propose a profit distribution scheme between LTE and DVB operators as well as TV channel providers, taking into account the subscription revenues as well as infrastructure and operational costs. We consider two cases: one in which both LTE and DVB networks are managed by a single operator and one in which the operators are separate. In both cases, we derive general closed-form expressions for

each player profit share using coalition game concept Shapley value. We show how we can adapt these general results to other market implementations than the proposed cooperative one: a market led by LTE and another one led by DVB.

We extend the economical study in Chapter 5, where we present, first, strategic investment framework considering DVB-only network where the decision is whether to deploy the network or not, and if yes, when to do so, taking into account the uncertainties related to demand and network operation cost. We extend, next, this framework in order to include in the investment decision, the reaction of the mobile network operator. The latter may decide to join cooperatively the broadcaster in the investment, bringing thus more customers and reducing the network cost.

In Chapter 6, we, eventually, conclude our work and introduce several future perspective

## Part I

# Hybrid DVB/LTE network for Mobile TV delivery: dimensioning and planning considerations



## Chapter 2

# Planning Mobile TV in DVB and LTE networks

Bringing TV to handheld devices is quite challenging. This service targets a wide range of "on move" receivers with small screens and limited power life.

In this context, the terrestrial broadcasting systems who have traditionally been in the business of broadcast TV, introduced some modifications to fit their platforms to the mobile world. European research efforts came up with the DVB-H technology, that added features such as: *Time slicing* for an enhancement in power consumption, *Multi Protocol Encapsulated Forward Error Correction* (MPE-FEC) for efficient frame encapsulation and data correction schemes, enhancing, thus, the reception quality and the *4K FFT* (Fast Fourier Transform) feature that combats the Doppler shift effect of frequencies while moving [6]. However, this technology, has not fulfilled the initial expectations due to the expensive dense DVB-H network that was needed then. Today, promising technologies are being discussed, namely DVB-T2-Lite and DVB-NGH.

In the meantime, the 3GPP systems were evolving and increasing their offered bitrates. And hence, Mobile TV is becoming a possible service to be delivered especially with the introduction of 3G+ technology LTE. The major concern regarding these cellular mobile systems is the presence of diverse types of services such as voice and data which have to be delivered in addition to the targeted Mobile TV ones.

Cooperation between broadcast and 3GPP cellular networks for an efficient delivery of mobile multimedia services has been considered with the introduction of DVB-H. We can identify, in this context, two research trends considering these hybrid broadcast/cellular networks

The first trend considered this cooperation as a mean to address the congestion issue in the unicast cellular network and introduced the DVB system for additional



capacity for multimedia services [14–19]. Authors in [15] considered for multimedia file download and proposed a smart algorithm to redirect some requests from cellular network to broadcast one based on a so-called "cost function" that takes into account the transmission time on both network bearers. Later on, a queuing analysis was done in [16] for this file download case, in a UMTS/DVB-H hybrid network, quantifying the impact of such a setting on the average response time. More developed load balancing strategies between broadcast (DVB-H) and cellular systems (UMTS) are presented in [17] and [18]. An inter-system handover decision that takes into account both quality of service and network operation costs is defined in [17]. Authors of [18] took into account a target Grade Of Service (GoS) and proposed a performance model and criteria bounds for load switching between UMTS and DVB-H for a streaming multimedia service.

The second research trend adopts a more DVB centric point-of-view, where the unicast cellular network is used to repair the DVB broadcast channel and enhance thus the DVB robustness without increasing its power and infrastructural costs [20, 21].

Although the results of the previously discussed studies were ambitious and pointed out interesting benefits that broadcast and cellular operators can get if they consider cooperation for a common offer of multimedia service; the hybrid DVB-H/UMTS network was not successfully deployed. This failure was mainly related to economic problems. In fact, most of the cooperation studies considered a scenario where the service area is fully covered by both DVB and cellular networks, and new DVB-H sites were, therefore, needed [22]. This densely needed DVB-H network, purely dedicated to mobile TV services, is not economically justified unless user demand is high.

This is why we address in this thesis the cooperation between broadcast and cellular networks considering a mutual coverage strategy unlike previous works which were mostly limited to their capacity management.

We describe in the section 2.1, the emerging mobile DVB technologies (DVB-T2 Lite and DVB-NGH) and explore the planning requirements of Mobile TV delivery via these networks. We then investigate in Section 2.2 the LTE system and we propose a resource sharing policy between Mobile TV and its already delivered services (voice, video, data etc.). We propose further a hybrid DVB/LTE network in Section 2.3 and investigate, eventually, the QoS of Mobile TV in Section 2.4.

## 2.1 Planning considerations in mobile broadcast networks

### 2.1.1 Overview of the technologies

#### 2.1.1.1 Lessons learnt from DVB-H

DVB-H is the main reference for bench-marking when discussing any new handheld technology of the Digital Terrestrial Television (DTT) community. In this thesis we are mainly interested in network planning and dimensioning issues and two important lessons, in this context, can be learnt from the DVB-H experience:

- **Lesson 1:** The provision of fixed and mobile TV services from a shared infrastructure is a winner strategy.
- **Lesson 2:** A flexible service specific robustness is an essential feature for a low cost, rich multimedia delivery.

In fact, since the first attempt of Mobile TV delivery with DVB-H, broadcast operators were mainly concerned about the needed infrastructure cost to deliver this new service especially in its initial stage.

DVB-H standardization took these worries into account and introduced the option of “in band” mobile delivery [6]. This option enables to transmit DVB-H signals, targeting mobile receiver, over the already existent DVB-T infrastructures in a frequency multiplexing way with the latter technology signals, targeting fixed receiver. However, this solution was not as successful as expected, because DVB-T and DVB-H signals share the same transport stream and must have, thus, the same transmission mode (FFT size, Guard Interval (GI) and modulation and code rate). These latter parameters, defining the transmission mode, were imposed by the DVB-T requirements, the base service of this network, and were suitable for fixed rooftop antennas reception but not for mobile ones with poor receiving gains and especially indoor users who suffer from severe attenuation. The solution was in deploying a dedicated DVB-H mobile network with transmission parameters fully planned for handheld reception. However, it was proved in [22] that a dense number of sites is needed to increase the coverage and the capacity of offered mobile TV services. Operators were not able to recover these additional needed infrastructure investments and were hence not motivated to deploy this Mobile TV network.

Hierarchical transmission is another solution, introduced by the DVB-H standard, to overcome the problem of coverage gap between fixed and mobile services without

the need for separate infrastructures. With this option, DVB-T and DVB-H services are transmitted in two independent transport streams in the same radio frequency channel, where one stream known as High Priority (HP) is embedded within a Low Priority (LP) one [6]. The HP streams are more robust than LP ones and can be used to increase DVB-H coverage, but these latter services pay an increased penalty in their Carrier to Noise ratio (C/N) and some capacity limitations in comparison with the non hierarchical modulation case [23][24]. Nevertheless, the service specific robustness was an interesting idea, but was not a hit in DVB-H technology due to its capacity limitation and its complicated implementation in transmission as well as reception. And so, a more flexible service specific robustness scheme is needed, especially that any new mobile broadcast technology will target a large variety of user conditions requiring reception-specific modulation schemes.

#### 2.1.1.2 The next handheld evolution of DTT

In 2008, the European Broadcasting Union (EBU) published the standard of the second generation digital video broadcasting for terrestrial reception DVB-T2 [8][9] that targeted fixed and portable High Definition (HD) services and aimed to offer an increase in capacity of 30 % in comparison to the previous technology DVB-T [25]. It is an ambitious technology promising a better performance for fixed, portable and Mobile reception thanks to many improvements in modulation and error protection schemes as well as in physical layer and framing structure.

DVB-T2 standard takes into consideration **lesson 1** introduced in the previous section, and defines a Time Division Multiplexing (TDM) framing structure, where the delivered signal is a succession of T2-Base Frames carrying DVB-T2 fixed reception signals and Future Extension Frames (FEF) carrying data with totally different transmission parameters (FFT size, etc) and suitable for other reception needs such as mobile reception [8]. A new era of in band mobile broadcasting has thus begun with DVB-T2 where both fixed and mobile share the same multiplex in a very flexible way without any limitations imposed by one on the other.

Another important feature in the DVB-T2 technology is the Physical Layer Pipe (PLP), which is a transparent physical layer that enables service specific robustness feature. Multiple services can be carried, thus, in the same frame, each in an independent PLP with different modulation and code rate schemes (MCS) for a diversified coverage (for local/regional services integration), reception environment (indoor/outdoor) and/or type of receivers (fixed/portable, different capacity requirements, etc)[8][26]. This flexible reception-specific modulation goes along with what is introduced in the previous section as being **lesson 2**.

DVB-T2 standardization included a mobile profile, known as T2-Lite [8], as being a subset of DVB-T2 with some extensions to target handheld devices. However, the real next-generation mobile multimedia broadcasting technology is introduced with DVB-NGH. This latter is presented by the DVB chairman as being a two phase technology [1]: in a first phase it inherits many features from DVB-T2 Lite and enhances it with advanced technologies such as Multiple Input Multiple Output (MIMO), Scalable Video Coding (SVC) and an optional satellite component. In a second phase, it is intended to converge/cooperate with 3GPP cellular network such as LTE.

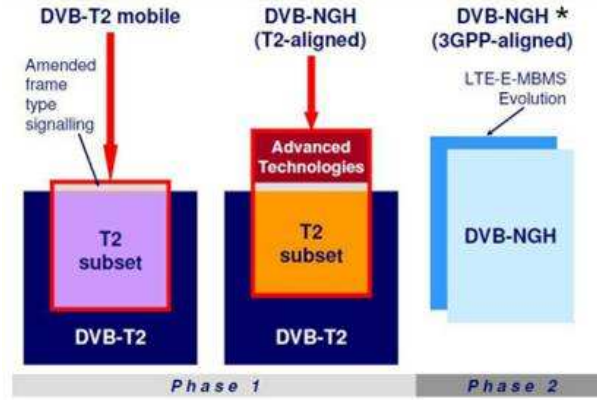


Figure 2-1: DVB-NGH development phases as introduced by the chairman [1]

The physical layer specification of DVB-NGH was finally published in November 2012 [10]. It surpasses its predecessor DVB-H by its throughput performance and most importantly by its flexibility and its efficient reuse of existent infrastructure as well as bandwidth.

### 2.1.2 Dimensioning study

The dimensioning of a DVB network offering Mobile TV services consists of two phases: coverage and capacity planning.

As mobile signals of the emerging DVB technologies (DVB-T2 Lite and DVB-NGH) are intended to be broadcast in the FEF part of a DVB-T2/NGH multiplexed signal, mobile TV network will use the existent DVB-T2 infrastructure. And so, the number of transmitters and their positions are known and fixed by the deployed DVB-T2 network planned for fixed TV reception. Each transmitter has to serve, thus, a given area of radius  $R_s$  given by:

$$R_s = \frac{ISD}{2 \cdot \cos(30)} \quad (2.1)$$

with  $ISD$  the fixed Inter-Site Distance.

Given this, the first phase in the dimensioning of the emerging DVB network would be the coverage planning if the network design is limited by the available transmission power. In this case, we determine, first, the best modulation and code rate scheme (MCS), that is able to cover the service region of each transmitter, given the transmission power, and derive then the capacity planning phase that takes as input this optimal MCS and estimates the network capacity in terms of served TV channels. If, however, the operator targets a given number of TV channels whatever the cost, the capacity planning would be the first phase: we determine, hence, the MCS that offers the required capacity resources, and derive next the coverage planning phase to estimate the required transmission power.

### 2.1.2.1 Coverage requirements

To have a good coverage, a minimum required C/N of a modulated signal carrying TV services has to be ensured. For lower C/N, this signal will be so noisy and erroneously decoded. We hence begin by link budget analysis and derive the maximal permitted signal degradation due to the transmission trajectory, known as pathloss, for a given transmission power, a MCS scheme, propagation environment (indoor/outdoor) and reception condition (rooftops terrestrial services or handheld mobile TV) [25] as depicted in Table 2.1.

The coverage area can then be obtained depending on the propagation model. We use the Okumura-Hata propagation model and its ITU-R P.529-3 modification, for covered distance above 20 Km [27], and present in Figure 2-2 the coverage radius as a function of transmission powers, for Rayleigh mobile indoor services. We present three modulation schemes: 64-QAM 2/3, 16-QAM 3/5 and QPSK 3/5 whose C/N ratios are equal to 15.7 dB, 9.3 dB and 3.5 dB respectively. We compare them to a Rice channel signal targeting fixed reception and modulated by 256-QAM 2/3 requiring a C/N of 17.8dB.

Let us note, first, that DVB-NGH is still in standardization phase and we lack many experimental parameters, such as C/N. The considered parameters are, hence, those of DVB-T2 Lite in Single Input Single Output (SISO) mode in Rayleigh channel for portable indoor reception for a bit error rate (BER) of  $10^{-4}$  [28]. The improvement in DVB-NGH signal will certainly improve the C/N ratio and hence the covered area, but the investigations and discussions contained in this thesis will still remain the same.

Even with the improvements in modulation and error protection of DVB-T2 Lite, we can deduce from figure 2-2, that, given a transmission power, there will always

	DVB-NGH*	Fixed***
EIRP [dBm] (a)	$P_D$	$P_f$
Receiver Noise [dBm] (b)	-99.11	-99.11
required C/N [dB]	$(C/N)_D$	$(C/N)_f$
Receiver sensitivity [dBm] (d)	$(b) + (C/N)_D$	$(b) + (C/N)_f$
Antenna Gain [dBi] (e)	0	12.15
Cable Loss [dB] (f)	0	4
Total Receiver Gain [dBm] (g)	$(d)-(e)+(f)$	
building/vehicle loss [dB] (h)	8	0
s.d. building loss [dB] (i)	6	0
standard deviation (s.d.) [dB] (j)	5.5	5.5
Total standard deviation [dB] (k)	$\sqrt{(i)^2 + (j)^2}$	
Distribution Factor (l)	it depends on the target coverage probability ( $\mu_c$ ). It is equal to 1.64 when $\mu_c = 95\%$ and 2.33 for $\mu_c = 99\%$	
Correction factor [dB] (m)	$(k) \cdot (l)$	
Total Margins [dB] (n)	$(h) + (m)$	
PathLoss [dB] (o)	$(a) - (g) - (n)$	

Table 2.1: Coverage Planning Parameters

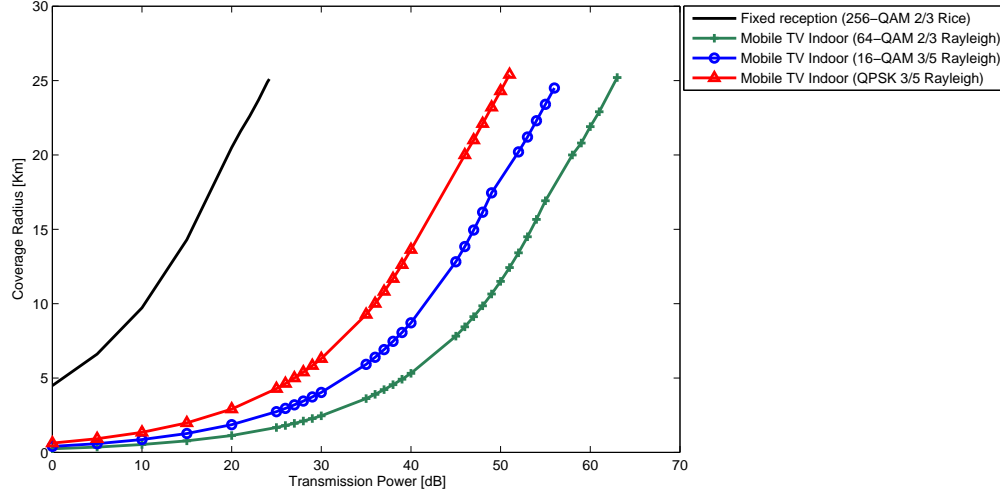


Figure 2-2: The required transmitter power  $P_D$  function of the target coverage radius and PLP modulation

be a gap between the fixed and mobile TV coverage as in the case of the DVB-H technology. This is in fact due to transmission penalties between rooftop and indoor handheld reception. However, the TDM frame structure could allow the possibility of transmitting the mobile services carried in the FEF with a different transmission

power than the fixed one carried in the T2-base frames. This variation in transmission power could help somehow decreasing this gap. This was not possible with the DVB-H technology multiplexed in a frequency division way with the DVB-T fixed services.

### 2.1.2.2 Capacity requirements

The other phase in the planning is capacity planning in order to determine the maximal number of served TV channels given a modulation and code rate scheme. We begin by describing the available resources and explore next the sharing strategy and the resultant admission condition.

#### Available resources:

DVB-T2 Lite (or DVB-NGH) services (TV channels) are transmitted in the FEF part of a DVB-T2 superframe (Fig. 2-3), each in an independent PLP. The NGH frame is defined in [10] as being a succession of Orthogonal Frequency Division Multiplexing (OFDM) symbols, carrying signaling and data information. The number of these symbols depends on the frame length, denoted by  $T_F$ , the guard interval and the used FFT size.

As we are dealing with OFDM modulation, each OFDM symbol is modulated over a given number of carriers, whose number depends on the used FFT size. The value of this symbol on a given sub-carrier defines what we call an OFDM cell and it might carry a signaling or a Mobile TV data. The number of cells that can carry useful data are called active cells and their number in a symbol depends on the logical type of this symbol (see [9][10]), the number of served PLP within the frame, denoted by  $n_{PLP}$ , and the FFT size.

And so, one can say that a NGH frame offers a number of useful active OFDM cells,  $C_{useful}(T_F, n_{PLP})$ , that depends on the frame duration, the number of served PLP in the system and the signal FFT and the system maximal useful capacity in OFDM cells per second which is given by:

$$C_{max}(T_F, n_{PLP}) = \frac{N_{FEF} \cdot C_{useful}(T_F, n_{PLP})}{T_{SF}} \text{ [cells/s]} \quad (2.2)$$

where  $N_{FEF}$  is the total number of NGH frame in a superframe,  $T_F$  is the FEF duration,  $n_{PLP}$  is the number of served PLP and  $T_{SF}$  is the superframe duration.

#### Sharing strategy:

The derived total number of OFDM cells have to be shared by all TV channels (in other words by PLPs) as depicted in Figure 2-3.

Each PLP is sliced into Forward Error Correction (FEC) blocks of 16200 bits each, which define the unit block of bits that should be processed for scheduling. The

number of OFDM cells available in a FEC block, denoted by  $N_{cell}$ , depends hence on the PLP modulation (MOD)(eg, for 16 –  $QAM$  modulation a FEC block contains  $N_{cell} = \frac{16200}{\log_2(16)} = 4050$  [cells]).

Let us note that the useful data bits available in a FEC block is given by  $(K_{bch} - BB_{Header})$ , where  $K_{bch}$  is the number of bits processed by the FEC coding subsystem to generate a FEC block and  $BB_{Header}$  is a 3, 5, 6 or 8-byte header [10].  $K_{bch}$  depends on the PLP Code rate (CR).

Given all this, the number of FEC blocks per second needed by a PLP carrying a TV channel of bitrate  $d_{TV}$  is given by:

$$N_{FEC}(d_{TV}, CR) = \frac{d_{TV} \cdot T_{SF} + I_B}{T_{SF} \cdot (K_{bch}(CR) - BB_{Header})} [block/s] \quad (2.3)$$

where  $d_{TV}$  is the TV channels required bitrate,  $T_{SF}$  is the superframe duration,  $d_{TV} \cdot T_{SF} + I_B$  are the required bits to be carried formed by  $d_{TV} \cdot T_{SF}$  bits representing the total data bits of a TV stream in a superframe and  $I_B$  bits for in-band signaling and  $K_{bch}(CR) - BB_{Header}$  are the total useful bits carried by a FEC block.

As a result, the number of OFDM cells per seconds that should be allocated for a given PLP depends on its modulation and code rate schemes and is given by

$$N_{FEC}(d_{TV_i}, CR_i) \times N_{cell}(MOD_i) \quad [cells/s]$$

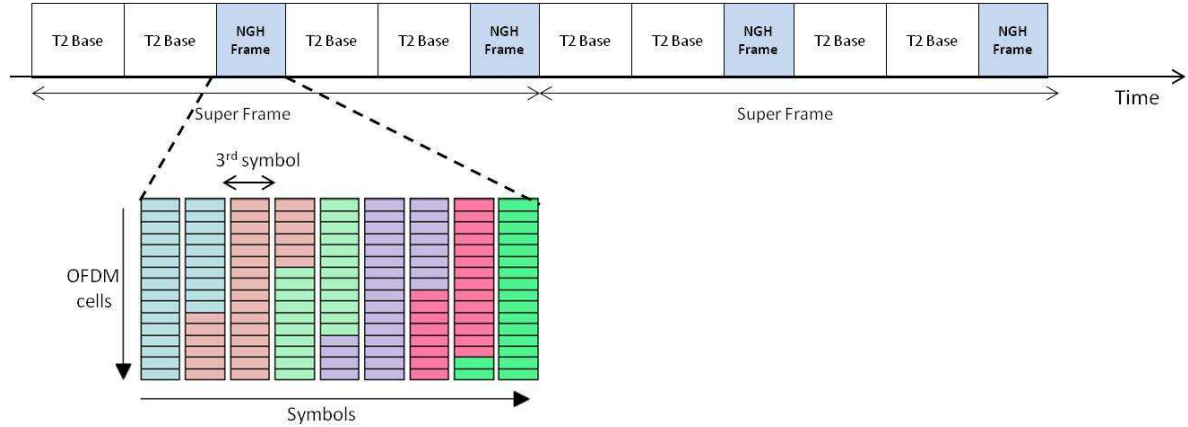


Figure 2-3: DVB-T2/NGH Superframe

#### Admission Condition:

Finally the mobile DVB capacity in terms of the maximal number of served TV



channels is given by:

$$\max\{N_{TV} \in \mathbb{N} : \sum_{i=1}^{N_{TV}} N_{FEC}(d_{TV_i}, CR_i) \cdot N_{cell}(MOD_i) \leq C_{max}(T_F, N_{TV})\} \quad (2.4)$$

where  $N_{FEC}(d_{TV_i}, CR_i)$  is the required FEC block capacity that should be allocated to a PLP  $i$  of useful bitrate  $d_{TV_i}$  and a code rate  $CR_i$  (Eq.2.3 ),  $N_{cell}(MOD_i)$  is the number of cell in a FEC block when the correspondent PLP modulation is  $MOD_i$  and  $C_{max}(T_F, N_{TV})$  is the DVB-T2 Lite (or DVB-NGH) system cell capacity (Eq. 2.2)

We consider, as an example, that the operator wishes to serve 7 TV channels targeting two device requirements: High definition (HD) services demanding 512 [kbps] and single definition (SD) ones demanding 250 [Kbps]. The SD channels have the highest priority and 7 SD TV channels must at least be served. We present in Table 2.2 the number of served TV channels for different modulation and code rate schemes, for a DVB-T2/NGH multiplexed signal whose superframe is composed of two successive T2-Base frames and one FEF of 250 ms each.

MODCOD	SD channels	HD Channels
QPSK 3/5 (both SD and HD)	7	0
16-QAM 2/3 (both SD and HD)	7	5
64-QAM 3/5 (both SD and HD)	7	9
SD: 16-QAM 2/3 and HD: 64-QAM 3/5	7	7

Table 2.2: Capacity of the DVB-T2 Lite in terms of served TV channels for different modulation and coding schemes

Results shows that by serving the 7 higher priority SD TV channels, we are able to serve only 5 HD ones if we choose 16-QAM 2/3 modulation. We are able to serve all the 7 SD and HD channels if we increase the modulation order to (64-QAM 3/5). A third option is possible in emerging DVB-T2 Lite and DVB-NGH thanks to the PLP feature and its service specific robustness capability, where we will be able to serve the target SD and HD services by increasing the modulation order of the PLP carrying the HD services (SD: 16-QAM 2/3 and HD: 64-QAM 3/5).

## 2.2 Planning consideration for Mobile TV in LTE

### 2.2.1 Overview of LTE technology

Cellular mobile networks are the fastest growing systems in the telecommunication field. They migrated from pure voice transport systems to more developed ones

permitting data and multimedia transmissions. The popularity of these latter services has created real challenges regarding the operator bandwidth resources.

In this context, LTE has been developed by 3GPP in order to meet the increasing demand for mobile broadband services. It owes its success to several design parameters[4] [29]; it supports wide and scalable bandwidth (1.4, 3, 5, 10, 15 and 20 MHz) and very low latency in both user and control planes. LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink [30]. These techniques have led to higher spectral efficiency compared to previous 3GPP technologies, and give a peak rate of 100 Mbps in the downlink and 50 Mbps in the uplink.

With these improvements, LTE promises an efficient delivery of both real-time and non real-time services. In addition to the voice and best effort services, LTE operators attempt, nowadays, to offer video services and especially live ones constituting the heart of what is called Mobile TV services.

These operators started to provide video services for their customers by point to point bearer [31]. This solution was acceptable in the early stages of video delivery when the number of users was very low and video demands were limited to on demand streaming services. However, it is certainly not efficient for Mobile TV delivery and especially live services where a large number of users must be served at the same time. It is shown in [32] that this unicast strategy will rapidly congest the network even for a limited number of TV users and may degrade the performance of voice and data services.

This fact urges the need for 3GPP Multicast/Broadcast feature, where the content is transmitted over a single channel from the source to multiple users. This ability was introduced in the release 6 of UMTS with the Multimedia Broadcast Multicast Service (MBMS) technology [33][34] and an enhanced version was anchored next to LTE as Evolved-MBMS (e-MBMS) [4]. Recent releases of LTE propose the implementation of MBMS with Single Frequency Network (SFN) technology, where adjacent cells are synchronized to deliver simultaneously the same information to a given user so as to eliminate the destructive effect of interference especially at cell edges.

### **2.2.2 Modeling the resources sharing strategy between Mobile TV and LTE services**

As stated in the previous subsection, LTE is intended to support point-to-point, unicast services such as voice and data as well as broadcast ones such as mobile TV. These services have to share this OFDM-based technology common channel. This

latter is composed of a given number of adjacent, narrowband sub-carriers, of 15 KHz each, organized into chunks of 12 sub-carriers each and known as Physical Resource Blocks (PRB). A PRB is the smallest amount of resource a service can get. The maximum number of available PRBs, which we here denote by  $N_{RB_{max}}$ , varies with the LTE bandwidth [29].

Bandwidth [MHz]	1.4	3	5	10	15	20
Maximal number of PRBs	6	15	25	50	75	100

Table 2.3: Number of PRB for each LTE bandwidth

We consider in this work a general setting supporting three service types:

1. Real-time, unicast services, such as voice and video-conferencing, with a strict priority over other types of flows.
2. A mobile TV service composed of  $K$  TV channels to be broadcast, with a lower priority than the previous ones.
3. A best-effort, unicast service with the lowest priority of all.

We define, in the following sections, the PRB sharing scheme between the introduced services.

### 2.2.2.1 Resources for real-time unicast services

Real-time unicast calls are, as mentioned previously, the highest priority services and are thus served first. We consider that there are  $S$  different classes of these services and that each flow  $i$  of class  $s \in \{1, \dots, S\}$  requires an average bitrate of  $d_s$ .

The maximum throughput, which we denote by  $d_{RB}$ , that can be offered by a single PRB allocated to a unicast real-time user depends on its position in the cell and can be obtained based on static simulations that calculate the Signal-to-Interference plus Noise Ratio (SINR) at each position  $z$  and associate it to throughput  $d_{RB}(z)$ , using link level curves [35]. An example of this throughput is given in Fig. 2-4.

We model our LTE cell by  $U$  concentric circles areas around the base station and we denote by  $\overline{d_{RB}(u)}$  the average bitrate offered by a single PRB in area  $u \in \{1, \dots, U\}$ . As a result, a call belonging to class  $s$  for a user at position  $u$  will consume an average number of PRBs calculated by:

$$n_{RB}(s, u) = \frac{d_s}{\overline{d_{RB}(u)}} \quad (2.5)$$

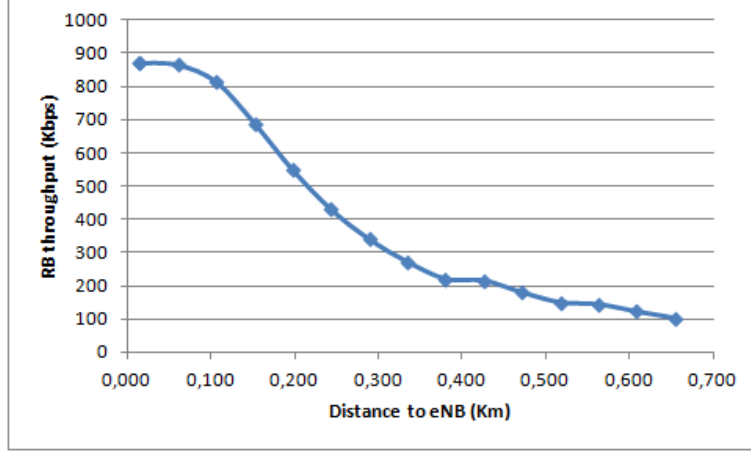


Figure 2-4: Resource Block throughput offered to LTE unicast services for different users' in different positions in the cell.

We are thus able to describe our network at each time instant by an admissible state  $\mathbf{a} = (a_{(s,u)} : s \in \{1, \dots, S\}, u \in \{1, \dots, U\})$  with  $a_{(s,u)}$  being the number of real-time, unicast service users of class  $s$  at position  $u$ . Let  $\mathbf{A}$  be the set of these admissible states where each state  $\mathbf{a} \in \mathbf{A}$  verifies the following admission control constraint:

$$\sum_{s=1}^S \left( \sum_{u=1}^U a_{(s,u)} \cdot n_{RB}(s, u) \right) \leq N_{RB_{max}} \quad (2.6)$$

with  $N_{RB_{max}}$  is the available number of PRBs in the LTE system (given in Table 2.3)

The evolution of these unicast services is modeled by a Continuous Time Markov Chain (CTMC), with  $(S \times U)$ -dimensional vectors, which are the admissible states  $\mathbf{a} \in \mathbf{A}$  verifying Eqn. (2.6) and representing the number of unicast real-time flows of each class  $s \in \{1, \dots, S\}$  at each position  $u \in \{1, \dots, U\}$ . Each of these classes is assumed to have a Poisson distributed arrival, with mean rate  $\lambda_s$ , and exponentially distributed service, with mean rate  $\mu_s$  that depends on class  $s$ . For simplicity, we suppose that the traffic intensity of each of them is uniformly distributed in the cell and the arrival rate at position  $u$  is then equal to  $\frac{\lambda_s}{U}$ .

The system stationary distribution, which gives the probability of each acceptable state  $\mathbf{a} \in \mathbf{A}$ , is given by a multi-Erlang distribution:

$$\pi_{\mathbf{E}}(\mathbf{a}) = G \cdot \prod_{s=1}^S \left( \prod_{u=1}^U \frac{E_{(s,u)}^{a_{(s,u)}}}{a_{(s,u)}!} \right) \quad (2.7)$$

where  $\mathbf{E}$  is the vector of traffic intensities of the  $S$  classes at the  $U$  positions in the cell,  $E_{(s,u)} = \frac{\lambda_s}{U \cdot \mu_s}$  [Erlang] and  $G$  is the normalization constant.

Eventually, given an acceptable unicast flow state  $\mathbf{a} \in \mathbf{A}$ , the remaining PRBs which would be allocated to mobile TV and best-effort data services are given by:

$$n_{RB_{remaining}}(\mathbf{a}) = N_{RB_{max}} - \sum_{s=1}^S \left( \sum_{u=1}^U a_{(s,u)} \cdot n_{RB}(s, u) \right) \quad (2.8)$$

### 2.2.2.2 Resources for mobile TV services

As stated earlier, Mobile TV service is broadcast in LTE thanks to the eMBMS feature and uses the SFN technology where cells are synchronized so that TV signals are received at the receiver with a low relative delay and can be viewed as copies of the same signal [36]. In this case, the classical SINR analysis is not sufficient as the nature of interference changes. Indeed, cells are grouped into clusters where transmissions from all cells are synchronized. Portions of the signals received from other cells, and that would have been counted as a pure destructive interference in unicast settings, are now viewed as useful signals [37].

Another major difference between broadcast and unicast transmission in LTE is that, in the latter, Adaptive Modulation and Coding (AMC) is used while, in the former, the same signal is transmitted to all users with the same Modulation and Coding Scheme (MCS) in all the network. A compromise is thus to be found, in SFN, between throughput and coverage (a robust MCS allows a larger coverage but with lower throughput). In this direction, authors in [36] derived special link level curves which associate to each cell radius the throughput achieved by 95% of users for each modulation and coding scheme.

The modulation to be used when we have a given cell radius  $R_L$  is the one that gives the highest throughput for this radius. To illustrate this point, let us consider Table 2.4 which is extracted from results of paper [36]. It shows, for a given cell radius, the modulation and coding rate to be used and the resulting throughput offered by an allocated PRB.

Cell Radius* $R_L$ [Km]	Optimal modulation and code rate	PRB offered throughput [Kbps] for 95% of users
0.2	64-QAM 3/4	500
0.36	64-QAM 2/3	467
0.46	16-QAM 2/3	300
0.5	16-QAM 2/3	260
0.6	QPSK 3/4	167

\*Results in [36] are given in terms of the Inter-Site Distance (ISD).  $r = \frac{ISD}{2 \cdot \cos(30)}$

Table 2.4: Optimal modulation and its correspondent offered throughput by a single PRB in e-MBMS with SFN mode for different cell radius

These throughput results will be used in our voice/TV/data shared LTE system, while keeping in mind that a considered PRB assigned for a TV channel by SFN, witnesses lower SNR than that calculated by the strategy in [36] due to the presence of high priority real-time unicast services. In fact, it may happen that an adjacent cell cannot assign the TV service to this PRB because there are higher priority flows to be served, increasing thus the interferences. This decrease in the SNR will lead to an increase in the Bit Error Rate (BER) which can, nevertheless, be enhanced by the presence of buffers at the receiver side.

Let  $\overline{d_{RB}^{SFN}}$  denote this throughput for a given cell radius. The number of PRBs allocated for a TV channel  $TV_j$  depends on its required bitrate. We note, here, that video services, while having a specified average bitrate (which we note by  $\overline{d_{TV}}$ ), are typically encoded using VBR scheme coupled with an appropriate rate control mechanism which adapts the actual bitrate to the content of the scene (for instance, action scenes are encoded with higher bitrates to conserve a target quality) while taking into consideration the available bandwidth resources. However, the operator must always guarantee to these services a minimum bitrate, so as to have an always on delivery with a minimum quality level [38]. This latter bitrate, which we denote by  $d_{TV}^{min}$  is the parameter that defines the admission control before applying statistical multiplexing policies to re-allocate the unused bandwidth to enhance the video quality[39].

Given this, the average PRB resources consumed by TV services are given by equation (2.9) and the maximal number of TV channel that can be served, when we have the state of real-time unicast flows  $\mathbf{a}$  is given by Eq. (2.10)

$$\overline{n}_{RBTV_j} = \frac{\overline{d_{TV_j}}}{d_{RB}^{SFN}(R_L)} \quad (2.9)$$

$$n_{TV_{served}}(\mathbf{a}) = \max\{k \in \{1, \dots, K\}\} : \sum_{j=1}^k n_{RBTV_j}^{min} \leq n_{RB_{remaining}}(\mathbf{a}) \quad (2.10)$$

with  $K$  the number of TV channels proposed by the operator and  $n_{RBTV_j}^{min} = \frac{d_{TV_j}^{min}}{d_{RB}^{SFN}(R_L)}$  is the minimal number of PRB that should be assigned to a TV channel.

We note that for the case of Constant Bit Rate (CBR) services, the required bitrate is stringent, and we will have  $d_{TV} = \overline{d_{TV}} = d_{TV}^{min}$ .

### 2.2.2.3 Resources for best-effort data traffic

Best-effort data services have the least priority. They are elastic and consume the remaining, if any, unused resources after serving the higher priority unicast real-time flows and mobile TV traffic.

Given unicast real-time flows state  $\mathbf{a}$  and a number of TV channels  $k = n_{TV_{served}}(\mathbf{a})$  (given by Eqn. (2.10)), the average number of remaining PRBs for best-effort services is given by:

$$\bar{n}_{RB_{BE_r}}(\mathbf{a}) = n_{RB_{remaining}}(\mathbf{a}) - \sum_{j=1}^k \bar{n}_{RB}^{TV_j} \quad (2.11)$$

where  $n_{RB_{remaining}}(\mathbf{a})$  is the remaining PRB resources after serving the real-time unicast flows at state  $\mathbf{a}$  (Eqn. (2.8)) and  $\bar{n}_{RB}^{TV_j}$  is the average number of PRBs consumed by TV channel  $TV_j$  (Eqn. (2.9)).

Elastic connections in progress in the system will share equally the remaining PRBs according to a Processor Sharing (PS) discipline. We assume that the dynamics of data traffic are faster than those of real-time unicast ones and mobile TV traffic. This implies that the sharing of resources by data flows is done for a given value of resources leftover by real-time unicast flows and mobile TV traffic. This is referred to quasi-stationary assumption in the literature [40]. And so, the steady-state distribution of the number of best-effort calls is given for a real-time calls state  $\mathbf{a}$  by:  $\mathbf{a}$  by:

$$Pr[n_{BE}|\mathbf{a}] = [\rho_{BE}(\mathbf{a})]^{n_{BE}} \cdot (1 - \rho_{BE}(\mathbf{a})) \quad (2.12)$$

where the average cell load  $\rho_{BE}(\mathbf{a})$  is defined as:

$$\rho_{BE}(\mathbf{a}) = \min\left\{\frac{A_{BE}}{n_{RB_{BE_r}}(\mathbf{a}) \cdot \overline{d_{RB}}}, 1\right\} \quad (2.13)$$

and where  $A_{BE}$  is the best-effort traffic intensity and  $\overline{d_{RB}}$  is the harmonic average of the PRBs throughput, averaged over the cell surface [35]:

$$\overline{d_{RB}} = \left(\sum_{u=1}^U \frac{p(u)}{d_{RB}(u)}\right)^{-1} \quad (2.14)$$

with  $p(u)$  the proportion of the cell area with PRB throughput  $d_{RB}(u)$  and  $U$  the number of areas in the cell.

The average number of PRBs allocated to an active data user when the network state is  $\mathbf{a}$  is given by [41]:

$$n_{RB_{BE}}(\mathbf{a}) = \bar{n}_{RB_{BE_r}}(\mathbf{a})(1 - \rho_{BE}(\mathbf{a})) \quad (2.15)$$

And so, the average flow throughput of data traffic when the network state is  $\mathbf{a}$  is given by:

$$D_{BE}(\mathbf{a}) = \bar{n}_{RB_{BE_r}}(\mathbf{a})(1 - \rho_{BE}(\mathbf{a})) \cdot \overline{d_{RB}} \quad (2.16)$$

Note that when there are no remaining PRBs to serve data calls, Eqns. (2.13) and (2.15) give a load equal to 1 and a data throughput equal to 0, respectively.

Eventually, by averaging the latter calculated throughput over all the network states, we obtain the average user throughput for best-effort traffic:

$$\overline{D_{BE}} = \sum_{\mathbf{a} \in \mathbf{A}} D_{BE}(\mathbf{a}) \cdot \pi_{\mathbf{E}}(\mathbf{a}) \quad (2.17)$$

## 2.3 Hybrid broadcast/broadband network proposal

### 2.3.1 Motivation towards cooperation

#### Motivation of DVB system

Typically, energy costs are preponderant in a DVB network. The transmission power is, thus, the key parameter of comparison between possible network designs.

On the other side, even though emerging handheld DVB technologies can flexibly re-use the already existent broadcast sites offering traditional TV for rooftop fixed receivers to deliver its Mobile TV services (see section 2.1), a higher transmission power is needed for mobile services to cover the same service area of fixed TV (section 2.1.2.1).

For instance, the DVB-T2 Lite operator, targetting 7 TV channels in HD and SD, has to use 64-QAM 3/5 MCS (Table 2.2) and a transmission power of 30 [Kw] (Table 2.1 and Figure 2-2) to offer these services in a region with radius  $R_s = 7$  [km]. If, however, we investigate the SD: 16-QAM 2/3 and HD: 64-QAM 3/5 case, which became possible with the service specific robustness option, we conclude that the SD services will cover the whole area of radius  $R_s = 7$  [Km] for a transmission power of only 6.87 [Kw], but the HD services will only cover a central region of radius  $R_{HD} = 4.27$  [Km] around the transmitter. This case is not feasible in a standalone DVB-T2 Lite network unless the majority of the HD users are in the central region.

This suggests a motivation for DVB to consider cooperation with LTE network to extend its coverage without increasing too much its transmission power.

#### Motivation of LTE system

The main technical challenge faced by 4G operators is to guarantee the required capacity of the always on TV services without altering the QoS of the dynamic unicast services which are mainly the blocking probability for the real-time unicast services and the average offered throughput for data ones.



From a side, we notice from equation (2.8) that the available resources for mobile TV services are function of the demand of real-time unicast services. And so, to maintain an acceptable quality of service for mobile TV, LTE operator has to limit the amount of resources consumed by real-time unicast traffic in a single cell without affecting the blocking probability of those latter services or the average throughput of best-effort flows. This can be achieved, referring to equations (2.5) and (2.6), by increasing the bitrate offered by a PRB.

From another side, we note that this capacity boosting comes at a cost. In fact, the PRB offered bitrate increases by decreasing the cell radius (Fig. 2-4) and a higher number of LTE cells will be needed to cover the target service area.

Therefore, it seems interesting for LTE to consider cooperation with another broadcast network such as DVB and rely on it to serve TV service when and where it cannot itself serve it, without increasing the number of LTE base stations.

Given all this, We propose in the following a hybrid DVB/LTE network with a coverage extension strategy, where the broadcast (DVB-T2 Lite or DVB-NGH) and cellular (LTE) infrastructures are used jointly to define a common, low-cost Mobile TV network.

### 2.3.2 Hybrid system description

The service area is divided in an optimal way (economically speaking) into areas covered by DVB networks and others by LTE ones.

Given the energy price, the DVB transmission power is limited to cover only a portion of the transmitter coverage area and the LTE system, which is planned for almost a universal coverage, is used to deliver Mobile TV in the not covered portion. We recall that the transmitter service area is defined by the already planned and deployed fixed TV network (Eq. (2.1)). The mobile DVB coverage region (DVB-T2 Lite or NGH) is modeled as a circular area around the DVB transmitter, smaller than the fixed TV service area, which corresponds to the inner region in Fig. 2-5.

User terminals are assumed to have both 3GPP and DVB receivers and the hybrid LTE/DVB system operates as follows: in the inner region, LTE offloads its mobile TV traffic to existing DVB infrastructure and serves only its classical voice/data unicast services. On the other hand, DVB relies on LTE cellular sites to offer the mobile TV service in the outer region. Note that in the outer region, LTE has to upgrade its network to guarantee sufficient capacity so as to offer the mobile TV service without degrading the QoS of its unicast users (voice and data). Referring to section 2.2.2, we notice that the offered capacity by LTE resources increases by decreasing the cell

radius (Fig. 2-4 for unicast services and Table 2.4 for broadcast ones). This means that the LTE system has to add more sites in the outer region and that is why the resulting LTE deployment is not uniform, as depicted in Fig. 2-5.

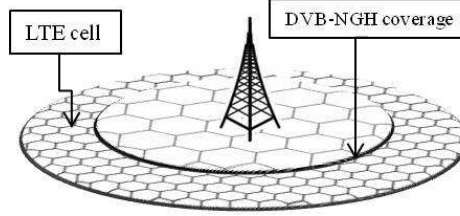


Figure 2-5: Proposed mobile TV service Area

However, to avoid over-dimensioning of the LTE network, we derive next QoS metrics for Mobile TV users, and propose to use them for a QoS-based planning of the LTE network.

On the other hand, the optimal radius of the inner region is tightly related to the prices of the DVB power consumption and the added LTE base stations. This study is deferred to Chapter 4.

## 2.4 Assessment of QoS metrics for Mobile TV service

The mobile TV performance is altered in the LTE region and, as explained in the section 2.2.2.2, it is mainly related to the state of the higher priority real-time unicast services. In fact, due to the dynamicity of these latter, LTE might not be always able to guarantee the sufficient PRB for TV users.

We previously defined the real-time unicast states as being a  $S \times U$ -vector denoted by  $\mathbf{a}$ , where  $a_{(s,u)}$  is the number of real-time, unicast service users of class  $s$  at position  $u$  and evolve according to a CTMC with Poisson distributed arrivals and exponentially distributed service times (section 2.2.2.1). In order to simplify the notation, we will adopt in the remainder of this thesis the following notations:

- $\mathbf{a} = \{a_i : i = (s, u) \forall s \in \{1, \dots, S\}, \forall u \in \{1, \dots, U\}\}$
- For  $i = (s, u)$ ,  $\lambda_i$  is the arrival rate of real-time unicast service calls of class  $s$  at area  $u$  of the cell and  $\mu_i = \mu_s$  is the service mean rate.

We consider that the operator aims to serve a set of channels denoted by  $K_{TV}$ . Let us note that TV channels do not usually have the same priority and that if the

remaining resources, after real-time unicast calls are served, are not sufficient to deliver all the TV channels, the operator will choose to broadcast the most popular ones (popularity is usually considered following a Zipf distribution [42]). A TV channel of class/priority  $k$  ( $TV_k$ ) is thus served if there are sufficient PRBs after serving unicast calls and TV channels of higher priority indexed from 1 to  $k - 1$ , i.e., if the following condition is satisfied:

$$n_{TV_{served}}(\mathbf{a}) \geq k \quad (2.18)$$

where  $n_{TV_{served}}(\mathbf{a})$  is the number of served TV channels given the real-time unicast state  $\mathbf{a}$  and obtained by Eqn. (2.10).

Let  $\mathbf{A}_k \subset \mathbf{A}$  be the set of admissible states  $\mathbf{A}$  whose elements satisfy Eqn. (2.18). It represents the set of unicast real-time flows that can be found in the network while this latter can still serve TV channel  $TV_k$ . So, for TV channel  $TV_k$ , two macro states are observed:  $\Theta_k$  with  $a \in \mathbf{A}_k$  where the TV channel of priority  $k$  is transmitted and  $\overline{\Theta_k}$  for  $a \in \overline{\mathbf{A}_k}$ , where the system does not have sufficient resources to serve it.

We recall that the unicast real-time flows state varies in the network according to CTMC defined in section 2.2.2.1 and LTE might not be able to serve Mobile TV users all the time. The probability of serving TV channel  $k$  is thus the sum of the probability of  $S \times U$ -vector states  $\mathbf{a} \in \mathbf{A}_k$ :

$$P_E(\Theta_k) = \sum_{\mathbf{a} \in \mathbf{A}_k} \pi_E(\mathbf{a}) \quad (2.19)$$

with  $\pi_E(a)$  the stationary distribution of real-time unicast services given in Eq. (2.7).

TV watching experience is affected by the frequency of serving interruptions and their durations. Interruption corresponds to a transition from  $\Theta_k$  to  $\overline{\Theta_k}$ . We hence define next its frequency and duration.

### 2.4.1 Duration of service interruption

The duration of an interruption is the holding time in  $\overline{\Theta_k}$ . We can define it in other words as being the time spent in  $\overline{\Theta_k}$  before hitting for the first time  $\Theta_k$ .

One possible way to calculate this holding time is to consider the discretized form of the continuous-time Markov chain describing the evolution of the unicast real-time states. The resultant Discrete Time Markov Chain (DTMC) is defined by the following transition probabilities:

$$q_{\mathbf{a}\mathbf{a}'} = \lambda_i \cdot \tau \cdot I_{\{a'_i = a_i + 1\}} + a_i \cdot \mu_i \cdot \tau \cdot I_{\{a'_i = a_i - 1\}} + (1 - \sum_{i=1}^{(S \times U)} (\lambda_i + a_i \cdot \mu_i) \cdot \tau) \cdot I_{\{\mathbf{a}' = \mathbf{a}\}} \quad (2.20)$$

where  $\lambda_i$  and  $\mu_i$  are the arrival and service rates of the  $i^{th}$  element in the unicast flows vector  $\mathbf{a}$ ,  $I_{\{C\}}$  is equal to 1 if condition  $C$  is true and 0 otherwise and  $\tau$  is the discretization time step which needs to be carefully chosen as described in Appendix A.

Given this, we recall the *hitting time* notion. For each state  $v = \mathbf{a}$ , we define  $m_{v \rightarrow \Theta_k}$  to be the number of time slots spent in  $\overline{\Theta_k}$  before we reach a given state  $v_1 = \mathbf{a}'$  in  $\Theta_k$ , starting from state  $v$  [43]. The latter reference defines the vector of hitting times  $m_{\Theta_k} = (m_{v \rightarrow \Theta_k} : \forall v)$  as being the minimal non-negative solution to the system of linear equations (Eqn. (2.21)). Let us note that minimality means that if  $y_{\Theta_k}$  is another solution of the system, we have  $y_{v \rightarrow \Theta_k} > m_{v \rightarrow \Theta_k} \forall v$ .

$$\begin{cases} m_{v \rightarrow \Theta_k} = 0 & \text{if } v \in \Theta_k \\ m_{v \rightarrow \Theta_k} = 1 + \sum_{j \in \overline{\Theta_k}} q_{vj} m_{j \rightarrow \Theta_k} & \text{if } v \notin \Theta_k \end{cases} \quad (2.21)$$

where  $q_{vj}$  is the transition probability from state  $v$  to state  $j$  defined in equation (2.20).

And so, the average number of time steps spent in  $\overline{\Theta_k}$  (interruption) during its sojourn is given by:

$$E[t_{\overline{\Theta_k}}] = m_{\Theta_k} \cdot p^T \quad (2.22)$$

with  $p^T$  the transpose of row vector  $p$ . The latter represents a probability distribution vector where  $p(v)$  corresponds to the probability that the sojourn begins at state  $v \in \overline{\Theta_k}$ . It is calculated in reference [44] and can be found in Appendix B.

Finally, the interruption duration  $D_{int}$  in units of time is obtained by multiplying  $E[t_{\overline{\Theta_k}}]$  by  $\tau$ :

$$D_{int} = E[t_{\overline{\Theta_k}}] \cdot \tau \quad (2.23)$$

## 2.4.2 Frequency of service interruption

The frequency of interruptions  $f$  is the number of interruptions per unit time. It is thus the expected number of visiting the set  $\overline{\Theta_k}$  in a given TV session (denoted by  $E[N^{\overline{\Theta_k}}]$ ) divided by the duration of this latter. In other words, given a period of time  $T = n \cdot \tau$ , where  $\tau$  is the discretization step (Appendix A), the QoS metric  $f$  is equal to:

$$f = \frac{E[N^{\overline{\Theta_k}}]}{n \cdot \tau} \quad (2.24)$$

**Proposition 1** *The frequency of interruptions is calculated by:*

$$f = \frac{P(\Theta_{\mathbf{k}})}{E[t_{\Theta_{\mathbf{k}}]} \cdot \tau} \quad (2.25)$$

where  $P(\Theta_{\mathbf{k}})$  is the probability of playing the TV channel at the receiver, given by Eqn. (2.19), and  $E[t_{\Theta_{\mathbf{k}}}]$  is the holding time (in number of time steps) in state  $\Theta_{\mathbf{k}}$  and is calculated in the same way we calculated the interruption holding time  $E[t_{\overline{\Theta_{\mathbf{k}}}}]$  in the previous subsection, simply by inverting the indices “ $\Theta_{\mathbf{k}}$ ” and “ $\overline{\Theta_{\mathbf{k}}}$ ” in Eqns. (2.21) and (2.22).

**Proof:** By definition,  $f = \frac{E[N^{\overline{\Theta_{\mathbf{k}}}}]}{n \cdot \tau}$ . And we can prove considering Lemmas 1 and 2 that  $E[N^{\overline{\Theta_{\mathbf{k}}}}]$  is given by:

$$E[N^{\overline{\Theta_{\mathbf{k}}}}] = \frac{n \cdot P(\Theta_{\mathbf{k}})}{E[t_{\Theta_{\mathbf{k}}]}} \quad (2.26)$$

□

**Lemma 1** *The average number of visiting  $\overline{\Theta_{\mathbf{k}}}$  (or average number of interruptions)  $E[N^{\overline{\Theta_{\mathbf{k}}}}]$  in the given duration  $T = n \cdot \tau$  is given by:*

$$E[N^{\overline{\Theta_{\mathbf{k}}}}] = n \cdot P(\overline{\Theta_{\mathbf{k}}}/\Theta_{\mathbf{k}}) \cdot P(\Theta_{\mathbf{k}}) \quad (2.27)$$

where  $P(\Theta_{\mathbf{k}})$  is the probability of being in  $\Theta_{\mathbf{k}}$  (Eqns. (2.19)) and  $P(\overline{\Theta_{\mathbf{k}}}/\Theta_{\mathbf{k}})$  is the conditional probability of  $\overline{\Theta_{\mathbf{k}}}$  starting from  $\Theta_{\mathbf{k}}$ .

**Proof:** Let  $N_{\Theta_{\mathbf{k}}}^{\overline{\Theta_{\mathbf{k}}}}$  be the expected number of visiting  $\overline{\Theta_{\mathbf{k}}}$  (no service) starting from  $\Theta_{\mathbf{k}}$  in the given duration  $T = n \cdot \tau$ . Using the indicator trick [45], and conditional average theory, the expected number of visiting  $\overline{\Theta_{\mathbf{k}}}$ , starting from  $\Theta_{\mathbf{k}}$  is given by:

$$\begin{aligned} E[N_{\Theta_{\mathbf{k}}}^{\overline{\Theta_{\mathbf{k}}}}] &= E\left[\sum_{l=1}^n 1_{\{S_l = \overline{\Theta_{\mathbf{k}}}/S_{l-1} = \Theta_{\mathbf{k}}\}}\right] \\ &= \sum_{l=1}^n E[1_{\{S_l = \overline{\Theta_{\mathbf{k}}}/S_{l-1} = \Theta_{\mathbf{k}}\}}] \\ &= \sum_{l=1}^n P(\overline{\Theta_{\mathbf{k}}}/\Theta_{\mathbf{k}}) \end{aligned} \quad (2.28)$$

where  $S_l$  is the system state at time slot  $l$ .

The considered Markov chain is homogeneous, and so the transition probability  $P(\overline{\Theta_{\mathbf{k}}}/\Theta_{\mathbf{k}})$  is the same whatever the time step  $l$ , and thus the average number of visiting  $\overline{\Theta_{\mathbf{k}}}$  starting from  $\Theta_{\mathbf{k}}$  is:  $E[N_{\Theta_{\mathbf{k}}}^{\overline{\Theta_{\mathbf{k}}}}] = n \cdot P(\overline{\Theta_{\mathbf{k}}}/\Theta_{\mathbf{k}})$ .

Finally, the average number of visiting  $\overline{\Theta_k}$  (or average number of interruptions)  $E[N^{\overline{\Theta_k}}]$  is obtained by multiplying the conditional expected number of visits  $E[N^{\overline{\Theta_k}}]$  by the probability  $P(\Theta_k)$  obtaining thus the target equation (2.27).  $\square$

**Lemma 2**  $P(\overline{\Theta_k}/\Theta_k)$ , the conditional probability of state  $\overline{\Theta_k}$  starting from state  $\Theta_k$  is given by:

$$P(\overline{\Theta_k}/\Theta_k) = \frac{1}{E[t_{\Theta_k}]} \quad (2.29)$$

where  $E[t_{\Theta_k}]$  is the average holding time (in time slots) spent in  $\Theta_k$ .

**Proof:** Let  $t_{\Theta_k}$  denote the number of time slots spent in  $\Theta_k$ . The probability that  $t_{\Theta_k}$  is equal to exactly  $l$  time slots is nothing but the probability that starting from  $\Theta_k$  we return in  $(l - 1)$  time slots to  $\Theta_k$  and move to  $\overline{\Theta_k}$  in the last time slot. It is given by:

$$\begin{aligned} P(t_{\Theta_k} = l) &= P(\Theta_k/\Theta_k)^{l-1} P(\overline{\Theta_k}/\Theta_k) \\ &= P(\Theta_k/\Theta_k)^{l-1} (1 - P(\Theta_k/\Theta_k)) \end{aligned} \quad (2.30)$$

We notice that  $t_{\Theta_k}$  is geometrically distributed with parameter  $(1 - P(\Theta_k/\Theta_k))$ . We hence obtain the average holding time  $E[t_{\Theta_k}]$  in Eqn. (2.29).

$$E[t_{\Theta_k}] = \frac{1}{1 - P(\Theta_k/\Theta_k)} = \frac{1}{P(\overline{\Theta_k}/\Theta_k)} \quad (2.31)$$

$\square$

## 2.5 Numerical illustrations and discussion

We consider a LTE cell of radius 0.5 Km, with a 5 MHz bandwidth ( $N_{RB}^{max} = 25$ ) serving a single real-time unicast class of voice calls requiring a bitrate of  $d_v = 50$  [Kbps] and best effort services. For this radius, the average throughput received by a PRB allocated for a unicast service is 237 Kbps (Fig. 1 and Eq. (2.14)). We aim to serve 7 TV channels of 512 Kbps each. We note that the LTE-SFN throughput offered by a PRB allocated for broadcast services (TV) is of 260 Kbps for a 0.5 Km radius (Table 2.4). We consider a TV session of 7 minute duration.

### Evaluation of QoS metrics

We plot in Figure 2-6 the probability that the user will not be able to visualize the TV channels. It is the probability that there are not enough resources at the base station to broadcast each TV channel because of higher priority voice calls, and higher

priority TV channels, if any. It is obtained by taking the complementary of equation (2.19).

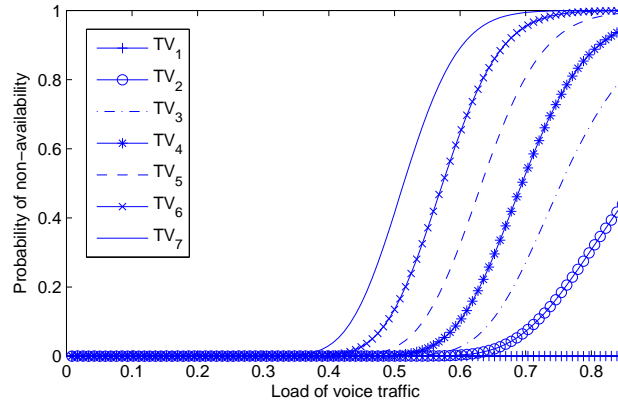


Figure 2-6: Probability of non availability of sufficient LTE resources to serve the TV channel of priority  $k$

As said previously, the leftover capacity, after serving the real-time unicast flows, is allocated to TV channels based on their priority levels, and so the lowest priority TV channel ( $TV_7$ ) will be the first channel to be cut off in case of resource scarcity; its degradation probability is the highest for a given voice traffic. In this particular example, the highest priority TV channel  $TV_1$  will be always served.

We present in Figures 2-7 and 2-8, respectively, the frequency and duration of degradation of  $TV_4$ .

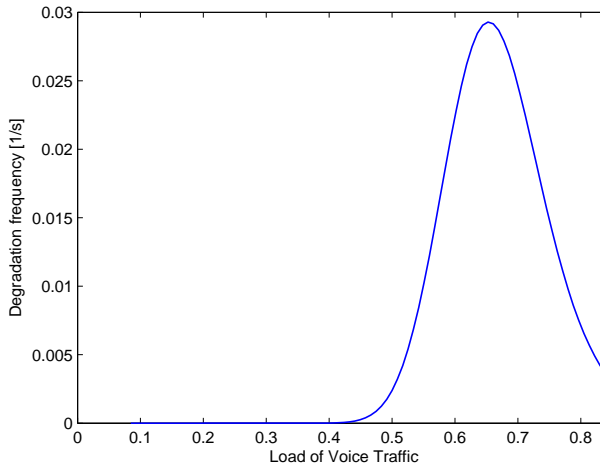


Figure 2-7: Frequency of interruption while watching  $TV_4$

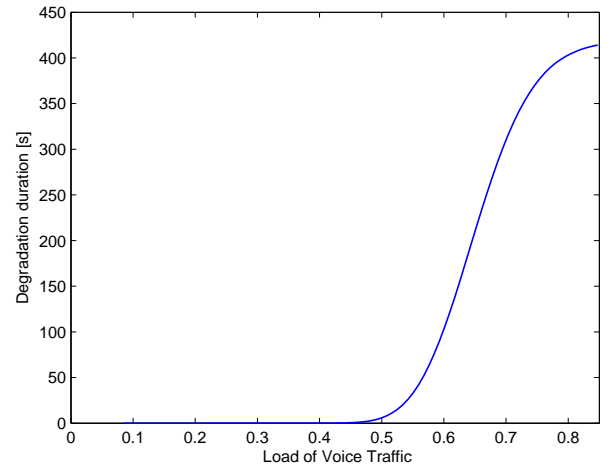


Figure 2-8: duration of interruption while watching  $TV_4$

Our results show that we need both metrics to dimension a network while min-

imizing the user non-satisfaction. In fact, for high traffic intensity, this frequency decreases and one might think, wrongly, that the user would enjoy a better watching experience. This is not true as, in this case, the degradation duration is high.

## Using the QoS metrics in LTE planning

The LTE planning process is defined as follow:

1. Inputs: Initial cell radius:  $R_L = R_0$  , real-time unicast requirements (offered traffic:  $E$  [Erlang/Km<sup>2</sup>], blocking probability:  $B_0$ ) and Data traffic (Intensity of offered traffic:  $A$  [Kbps], minimum required bitrate:  $D_0$ )
2. Calculate the QoS metrics and determine the maximal voice traffic intensity  $E_{max}$  that can be served while having the frequency and duration of TV interruption below certain thresholds.
3. if  $\frac{E_{max}}{\pi \cdot (R_L)^2} \geq E$  , the real-time unicast blocking probability  $B \leq B_0$  and the average data throughput  $D \geq D_0$ , the LTE network is good enough to serve the considered services. Otherwise, decrease the cell radius and repeat step 2-3

For example, we consider an initial LTE network with a cell radius  $R_0 = 0.5$  [Km] serving voice services, whose intensity is  $E = 120$  [erlang/Km<sup>2</sup>], with a blocking probability  $B_0 = 0.018$  and guaranteeing an average data throughput  $D_0 = 209$  [Kbps] for a data traffic intensity of 500 [Kbps].

The QoS of Mobile TV in this network when the operator targets 4 TV channels is given in Figure 2-9.

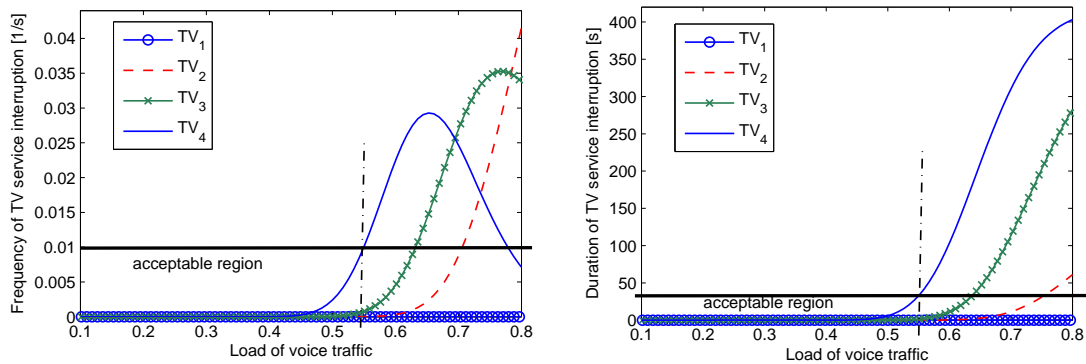


Figure 2-9: QoS metrics for 4 targeted TV channels when the LTE cell radius is  $R_L = 0.5$  [Km]

The voice traffic intensity has to be limited to 64.9 [Erlang] (82.6 [Erlang/Km<sup>2</sup>]) if the maximal acceptable interruption frequency in the TV service is limited to 0.01



[1/s] and the average interruption duration in the TV session is limited to 33.45 [s]. However, the offered service traffic intensity is of 120 [Erlang/Km<sup>2</sup>], and thus the Mobile TV QoS requirements could not be met.

Calculations showed that, the required QoS are met if we consider a LTE cell of radius 0.36. This latter network can serve a maximal voice traffic of 229.65 [Erlang/Km<sup>2</sup>] with the required blocking probability, while having an acceptable TV and data performances.

## 2.6 Conclusion

We proposed in this chapter a hybrid DVB/LTE network in a coverage extension scenario where DVB offers mobile TV (via DVB-T2-Lite or DVB-NGH) near the broadcast tower and LTE in the remainder of the network. This network implementation provides a continuation in the delivery of the Mobile TV service while using as much as possible the already existent infrastructures and helps, thus, both operators to decrease their infrastructure costs while offering Mobile TV services: DVB-T2 Lite (or eventually DVB-NGH) will not have to increase its expensive transmission power since it relies on LTE in the outer region and LTE offloads a part of its Mobile TV traffic on DVB-T2 Lite bearer and update its network in only a portion of the service area decreasing thus its cellular infrastructure costs.

However, the performance of this cooperative network is mainly related to the QoS of broadcast content delivered by the LTE network in the outer region, since they have to share bandwidth resources with other services. We have specifically derived the LTE network capacity in the presence of three types of flows: voice, TV and data, and calculated several performance metrics that quantify the QoS experienced by the mobile TV user, namely the probability that LTE has the sufficient resources to deliver mobile TV and hence the service continuity knowing the fluctuations of voice traffic in LTE.

The developed model can serve as a basis for DVB/LTE network dimensioning, given a target QoS. However, operators need to find the best compromise between users expectations and the required network infrastructure and costs. We propose, hence, in the next chapter to investigate the impact of playout buffers (usually present at the receiver side) on the derived QoS metric, as a way to combat the potential degradation in TV performance due to higher priority flows without over-dimensioning the network. We explore also the advantage of the presence of this buffer combined with file repair mechanism to combat errors and frame losses.

# Chapter 3

## Impact of playout buffer on the QoS

We investigate in this chapter the impact of the playout buffer at the receiver side on the service interruption of mobile TV due to the dynamicity of arrivals and departures of higher priority voice traffic as explained in the previous chapter.

We analyze the service performance from a user point of view and study in Section 3.2 the impact of the considered buffer on the previously derived QoS, namely the duration and frequency of service interruption.

We propose further in section 3.3 to exploit the existence of the buffer and the LTE feedback channels to request, if possible, retransmission of lost frames in case where the propagation channel is lossy and investigate the impact of this proposal on the frame loss probability.

### 3.1 Related works on multimedia playout buffering

In the literature, most of the papers that have tackled the impact of playout buffering on video quality in cellular networks focused on point to point unicast services, especially streaming ones, because it was widely observed that these services constitute the majority of multimedia demands over cellular networks whereas live broadcasting was at its infancy. Works in [46] and [47] for instance study the playout buffer at the *network* side in beyond 3G networks and define a dynamic buffer management scheme that guarantees the QoS of concurrent real-time and non real-time flows transported by the network.

Yet other works study the performance of the playout buffer at the *user* side,

again for streaming applications. For instance, the work in [48] proposes a general Markov channel model which uses information on the size of the video stream. This makes it inappropriate as a model for live traffic, which is the focus of our present work. Indeed, the main difference between streaming flows versus live ones is that the content of the former typically already exists, as in youtube for instance, whereas the latter content is created at the same time, or almost, as the user visualizing it. And so, in terms of buffering, there is less latitude to do so when the content is live.

Some works studied the performance of the playout buffer in the presence of streaming flows without considering the size of the content. Authors in [49] for instance modeled the end user playout buffer by a  $G/G/1/\infty$  or a  $G/G/1/N$  queue. They considered a diffusion approximation to explore the impact of flow dynamicity in the network on the buffer performance. An exact solution is derived in [50] using the transient behavior of the Markov chain describing the evolution of the number of connection demands in the system for Youtube-like streaming service. These works however did not consider sharing of resources with other types of flows. This sharing is an important feature in LTE networks which are meant to transport diverse types of applications with different priorities between them. In our work, we take into account the presence of real-time and data traffic in addition to live TV.

As far as live broadcast performance is concerned, most of the works do not focus on the playout buffer in such a context. The work in [51] for instance studied QoE of live traffic, using simulations, for different eMBMS design parameters. Very few works however consider the performance of the playout buffer in the context of TV transmission. Authors in [52] did so considering a two-state channel model known as Gilbert channel [53] which is suitable to model bursty packet losses due to path fading or user mobility. Their model however does not capture the effect of channel variations due to the dynamicity of higher priority voice traffic and its effect on the quantity of resources leftover to less priority TV traffic and which, at high load, constitutes the main reason for TV service interruption in cellular networks. And this is a major consideration in our work.

## 3.2 Case of non-lossy network

We investigate in this section the impact of the playout buffer on the QoS metrics developed in the previous chapter to describe the mobile TV performance; namely the frequency and duration of interruptions in mobile TV delivery due to the absence of resources at the LTE base station when they are totally consumed by higher priority real-time voice services. The impact of the playout buffer on service interruption due

to frame losses is differed to Section 3.3.

Since we are dealing with loss-less LTE broadcast signals in SFN, all users receiving TV channel  $TV_k$  from a given LTE cell, will have at each instant exactly the same buffer content (we neglect the propagation delay which is small compared to the buffer size). In fact, due to the broadcast mode, all the covered users of a cell will receive the same broadcast signal adapted to users experiencing worst radio conditions (typically users at the cell edge). And so, the evolution of system, which we present in this section for one user will be the same for all the users watching  $TV_k$  in the cell at each time instant.

### 3.2.1 Modeling of the playout buffer dynamics

The playout buffer size is expressed in terms of the amount of buffered playout duration. Let  $D_b$  denote the maximal duration of live content the buffer can store. The buffer dynamics are described by the following four phases:

- *Idle Phase:* It is a waiting phase where the playout buffer is empty and the TV channel is not transmitted on the air due to lack of resources (taken by higher priority voice flows in this case). This phase lasts until the network regains sufficient resources to transmit the target TV channel and the system moves then to the "Buffering only Phase".

If we denote the buffered content duration by  $b$ , this phase can be fully defined by the couple  $(\mathbf{a} \in \overline{\mathbf{A}_k}, b = 0)$  with  $\mathbf{a}$  the previously defined  $S \times U$ -vector representing the state of real-time unicast flows in the network (eq. 2.6) and  $\overline{\mathbf{A}_k}$  the subset of these states where the remaining resources for TV channels are not sufficient to deliver the  $k^{th}$  TV channel  $TV_k$  (i.e., does not verify Eqn. (2.18)).

- *Buffering only Phase:* It is triggered whenever the network regains the possibility to transmit the considered TV channel  $TV_k$  after an "Idle Phase". It starts from an empty buffer and the received content is pushed in the playout buffer while this latter is not fully loaded (the buffered duration is strictly less than  $D_b$  seconds). If an interruption in the transmission occurs in this phase before reaching  $D_b$ , the system moves directly to the "Service only Phase" in order to keep up with the live nature of the content and its playing. If however we reach the buffer full size, the system finds itself in the "Buffering and serving Phase".

So, this phase can be recognized by the couple  $(\mathbf{a} \in \mathbf{A}_k, 0 \leq b < D_b)$  with  $\mathbf{A}_k$  the subset of unicast states where the remaining resources for TV channels are

sufficient to deliver the  $k^{th}$  TV channel  $TV_k$  (Eqn. (2.18)).

The already introduced phases are considered to be the startup phases, where the receiver player is in holding state and does not stream contents even if the buffer is not empty. This is why we introduce a boolean parameter  $\omega$  that takes the value 0 if the buffered content are not streamed by the receiver player and 1 otherwise.

Another important observation is that if the order of the previously described phases is important at the beginning of the playout buffer cycle evolution, the sequence of the next described phases is tightly related to the dynamics of unicast voice traffic and there is no particular order between them.

- *Service only Phase:* This phase happens when the buffer is not empty but the TV channel is no longer transmitted over the air. It keeps playing the buffered content by pulling the buffered video frames until the network recovers its capability to offer the TV channel or the buffer becomes empty. The system will move to the "Buffering and serving Phase" in the first case and to the "Idle Phase" in the second one.

This phase is defined, thus, by the following parameters:  $(\mathbf{a} \in \overline{\mathbf{A}_k}, 0 < b \leq D_b, \omega = 1)$ .

- *Buffering and serving Phase:* During this phase, the receiver's player consumes content from the buffer while buffering newly received content in order to keep the delay constant. This phase lasts as long as the network has sufficient resources to transmit the target TV channel and is defined by :  $(\mathbf{a} \in \mathbf{A}_k, 0 < b \leq D_b, \omega = 1)$ .

Once an interruption in the transmission occurs, the system moves to the "Service only Phase".

## Steady-state probabilities

Given the previous explanations, we model the system states by the triplet  $v = (\mathbf{a}, b, \omega)$ . Where  $a, b$  and  $\omega$  are as defined above.

The transition between these states is governed by the unicast flow arrivals and service. The transition from state with buffered duration  $b_1$  to another state with buffered duration  $b_2$  can only take place at specific time instant  $T_2 = T_1 + |b_2 - b_1|$  given that the state with  $b_1$  took place at time  $T_1$ . And so, the system evolution cannot be described anymore by CTMC; we need to discretize it instead. The discretization step, denoted by  $\tau$ , should be carefully chosen:  $\tau$  should be chosen as large as possible

while guaranteeing that the unicast flow state will not change between two consecutive time slots. The optimal choice of  $\tau$  is explained in Appendix A.

As the network is observed each  $\tau$  time units, the buffer size can only take discrete values given by  $b = \eta \cdot \tau$  with  $\eta = \{0, 1, \dots, \frac{D_b}{\tau}\}$ . And the resultant Discrete Time Markov Chain (DTMC) will evolve as follows:

1. The system transition from a state belonging to "Buffering Only phase": ( $\mathbf{a} \in \mathbf{A}_k, b \leq D_b - \tau, \omega = 0$ ) is only possible to future states defined by ( $\mathbf{a}', b' = b + \tau, \omega' = I_{\{((\mathbf{a} \in \mathbf{F}_k) \& (\mathbf{a}' \in \overline{\mathbf{A}_k})) \text{ or } (b = D_b - \tau)\}}\}$ ) with  $I_{\{C\}} = 1$  if condition C is verified and 0 otherwise and  $\mathbf{F}_k$  the frontier states defined as being the set of states belonging to  $\Theta_k$  and leading to another state in  $\overline{\Theta_k}$  upon the arrival of a new unicast real-time call. Given Eqns. (2.18), (2.10) and (2.8), a given state  $\mathbf{a} \in \mathbf{F}_k$  verifies the following set of equations:

$$\left[ \sum_{i=1}^{|\mathbf{a}|} a_i \cdot n_{RB_i} + \sum_{j=1}^k n_{RB_{TV_j}}^{min} \right] \leq N_{RB}^{max} \quad (3.1)$$

$$\left[ \sum_{i=1}^{|\mathbf{a}|} a_i \cdot n_{RB_i} + \sum_{j=1}^k n_{RB_{TV_j}}^{min} + n_{RB_l} \right] > N_{RB}^{max} : l = 1 \text{ or } 2 \text{ or } \dots \text{ or } |\mathbf{a}| \quad (3.2)$$

In fact, the future state of a "Buffering only" state corresponds to changes from  $b$  to  $b'$  and from  $\omega$  to  $\omega'$ . For  $b'$ , the transition is equal to  $b + \tau$  because the buffer is filling up. As of  $\omega'$ , the transition is towards one of three possible states:

- Buffering only state: this is when the buffer is still filling up and did not reach  $D_b$  yet and there has been no interruption in content delivery from the base station. The user is not yet watching the content ( $\omega' = 0$ ). This transition happens when the buffer content  $b$  is strictly less than  $D_b - \tau$ .
- Buffering and serving state: this is when the buffer has been filled up, the user is watching the content ( $\omega' = 1$ ), and the buffer is also receiving new content from the base station. This is only possible if in the current state we have a buffer content equal to  $D_b - \tau$
- Serving only state: in this case, content from the base station has been interrupted due to lack of resources in the network, but the buffered content is played at the receiver ( $\omega' = 1$ ). This transition happens if the current state  $\mathbf{a}$  belongs to a frontier state  $\mathbf{F}_k$  and a unicast flow arrival takes place (see Eqns. (3.1) and (3.2)) leading the system to a state ( $\mathbf{a}' \in \overline{\mathbf{A}_k}$ ) where we cannot find sufficient resources to deliver  $TV_k$ .

And so, we obtain that  $\omega' = 1$  if  $((\mathbf{a} \in \mathbf{F}_{\mathbf{k}}) \& (\mathbf{a}' \in \overline{\mathbf{A}_{\mathbf{k}}}))$  or  $(b = D_b - \tau)$  and 0 otherwise.

2. The transitions from a state belonging to "Buffering and Serving" states ( $\mathbf{a} \in \mathbf{A}_{\mathbf{k}}, b > 0, \omega = 1$ ) are only possible towards states of the form  $(\mathbf{a}', b' = b, \omega' = 1)$ .

In fact:

- The buffered duration will remain the same because in this case the network can transmit content and the duration of received content at the buffer input is equal to the duration of played content at the receiver (buffer output). This is because live contents are not pre-stored, and if they are produced with a rate of  $B$  [frame/s], they have to be transmitted and played with this same rate to conserve jitter.
  - The content is always played at the receiver  $\omega' = 1$  even if the next unicast state does not allow the transmission of the TV channel ( $\mathbf{a}' \in \overline{\mathbf{A}_{\mathbf{k}}}$ ) because the buffer is not empty ( $b > 0$ ).
3. The possible transitions from "Service Only" states ( $\mathbf{a} \in \overline{\mathbf{A}_{\mathbf{k}}}, b > 0, \omega = 1$ ) are towards state defined by:  $(\mathbf{a}', b' = b - \tau, \omega' = I_{\{b \neq \tau\}})$ , because the buffered duration decreases with  $\tau$  as content is pulled and played by the receiver, so the next buffer state will be  $b' = b - \tau$ . On the other hand,  $\omega'$  will be equal to 0 only if the next state is an empty buffer  $b' = 0$ . This means  $b$  was equal to  $\tau$ .
  4. The transition probabilities from an Idle state ( $\mathbf{a} \in \overline{\mathbf{A}_{\mathbf{k}}}, b = 0, \omega = 0$ ) is somehow evident, since the buffer will be always empty ( $b' = 0$ ) and there is nothing to be played by the receiver ( $\omega' = 0$ ).
  5. Eventually, these transition probabilities will be equal to  $\lambda_i \cdot \tau$  if we have a class  $s$  arrival ( $a'_i = a_i + 1$ ) and  $a_i \mu_i \cdot \tau$  if we have a departure ( $a'_i = a_i - 1$ )

Taking into account all the above descriptions, we define next the transition probability matrix  $\mathbf{Q}_{\mathbf{b}}$ , where  $Q_b(v, v_1)$  defines the transition probability from state  $v$  to state  $v_1$ :

- Buffering Only states ( $\mathbf{a} \in \mathbf{A}_{\mathbf{k}}, b \leq D_b - \tau, \omega = 0$ ):

$$\begin{aligned}
 Q_b((\mathbf{a}, b, 0), (\mathbf{a}', b + \tau, I_{\{((\mathbf{a} \in \mathbf{F}_{\mathbf{k}}) \& (\mathbf{a}' \in \overline{\mathbf{A}_{\mathbf{k}}}) \text{ or } (b = D_b - \tau))\}})) &= \lambda_i \cdot \tau \cdot I_{\{(a_i \neq N_{maxi}) \text{ and } (a'_i = a_i + 1)\}} \\
 &+ a_i \cdot \mu_i \cdot \tau \cdot I_{\{(a_i \neq 0) \text{ and } (a'_i = a_i - 1)\}} \\
 &+ (1 - \sum_{i=1}^{|\mathbf{a}|} (\lambda_i + a_i \cdot \mu_i) \cdot \tau) \cdot I_{\{\mathbf{a} = \mathbf{a}'\}}
 \end{aligned} \tag{3.3}$$

- Buffering and Serving states ( $\mathbf{a} \in \mathbf{A}_k, b > 0, \omega = 1$ ):

$$Q_b((\mathbf{a}, b, 1), (\mathbf{a}', b, 1)) = \lambda_i \cdot \tau \cdot I_{\{(a_i \neq N_{max_i}) \text{ and } (a'_i = a_i + 1)\}} + a_i \cdot \mu_i \cdot \tau \cdot I_{\{(a_i \neq 0) \text{ and } (a'_i = a_i - 1)\}} \\ + (1 - \sum_{i=1}^{|\mathbf{a}|} (\lambda_i + a_i \cdot \mu_i) \cdot \tau) \cdot I_{\{\mathbf{a} = \mathbf{a}'\}} \quad (3.4)$$

- Service Only states ( $\mathbf{a} \in \overline{\mathbf{A}}_k, b > 0, \omega = 1$ ):

$$Q_b((\mathbf{a}, b, 1), (\mathbf{a}', b - \tau, I_{\{b \neq \tau\}})) = \lambda_i \cdot \tau \cdot I_{\{(a_i \neq N_{max_i}) \text{ and } (a'_i = a_i + 1)\}} + a_i \cdot \mu_i \cdot \tau \cdot I_{\{(a_i \neq 0) \text{ and } (a'_i = a_i - 1)\}} \\ + (1 - \sum_{i=1}^{|\mathbf{a}|} (\lambda_i + a_i \cdot \mu_i) \cdot \tau) \cdot I_{\{\mathbf{a} = \mathbf{a}'\}} \quad (3.5)$$

- Idle states ( $\mathbf{a} \in \overline{\mathbf{A}}_k, b = 0, \omega = 0$ ):

$$Q_b((\mathbf{a}, 0, 0), (\mathbf{a}', 0, 0)) = \lambda_i \cdot \tau \cdot I_{\{(a_i \neq N_{max_i}) \text{ and } (a'_i = a_i + 1)\}} + a_i \cdot \mu_i \cdot \tau \cdot I_{\{(a_i \neq 0) \text{ and } (a'_i = a_i - 1)\}} \\ + (1 - \sum_{i=1}^{|\mathbf{a}|} (\lambda_i + a_i \cdot \mu_i) \cdot \tau) \cdot I_{\{\mathbf{a} = \mathbf{a}'\}} \quad (3.6)$$

where  $\mathbf{a}$  is, again, the state of real-time unicast flows (Eqn. (2.6)),  $\mathbf{F}_k$  is the set of states verifying Eqns. (3.1) and (3.2) and  $I_{\{C\}} = 0$  if condition  $C$  is not valid and 1 otherwise.

**Example 1** *In order to illustrate the described system evolution and clarify the considered Markov chain, we consider a simple example, where we have a single real-time unicast class (voice) and a single TV channel to be broadcast. For the sake of illustration, we consider that the TV channel can be served when the number of voice calls is less or equal to 4 and the buffer size  $b_{max} = 2$ .*

*The system state is described by the triplet  $(n, b, \omega)$  where  $n$  is the number of voice calls,  $b$  is the buffered content and  $\omega$  is a boolean parameter that is 1 if the content is played by the receiver and 0 otherwise. The buffer dynamic states as well as the system transition probabilities are illustrated in Figure 3-1.*

*We note that the states  $(4, 0, 0), (4, 1, 0), (4, 1, 1)$  and  $(4, 2, 1)$  constitute what we call the border states.*

Finally, the stationary distribution of each state  $(\mathbf{a}, b, \omega)$  is denoted by  $\Pi(\mathbf{a}, b, \omega)$  and calculated by :

$$\Pi = \Pi_0 \cdot \lim_{n \rightarrow \infty} (\mathbf{Q}_b)^n \quad (3.7)$$



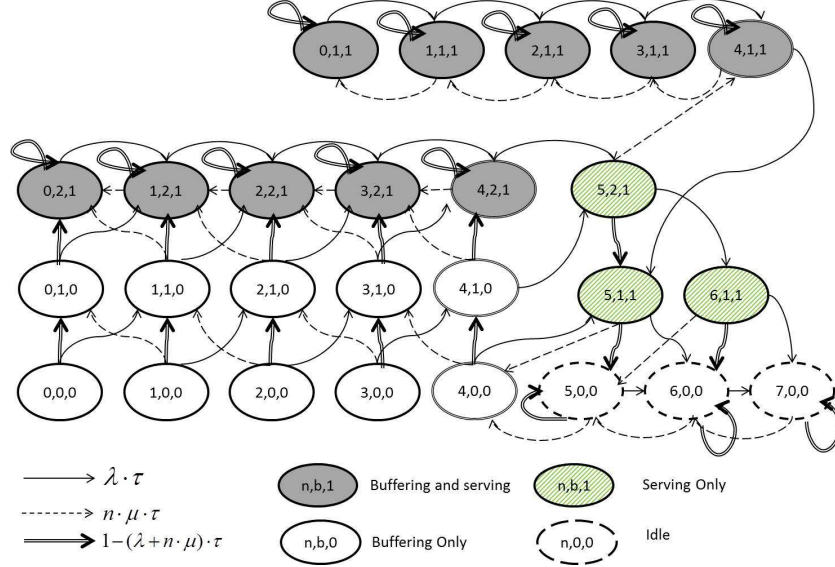


Figure 3-1: Example of the Markov chain of the buffer system

where  $\mathbf{Q}_b$  is the transition probabilities matrix defined in equations (3.3), (3.4), (3.5) and (3.6) and  $\Pi_0$  is the initial state distribution (no doubt the system evolution will begin by a state ( $\forall \mathbf{a}, b = 0, \omega = 0$ )).

Let us note here that as we are evaluating the performance in the steady state, we can from the beginning eliminate transient states (states that does not have any arrival input, such as states  $(0, 0, 0)$ ,  $(1, 0, 0)$  etc. in Figure 3-1), and obtain the steady state distribution by  $\Pi \cdot \mathbf{Q}_b = \Pi$ .

### 3.2.2 QoS metrics

As for the case with no buffer (Section 2.4), the system states, for each TV channel  $k$ , can be partitioned into two macro states:  $\Theta_k$ , which is the ensemble of previously defined states with  $\omega = 1$  (states corresponding to equations (3.4) and (3.5)) and it corresponds to states where the TV channel is played at the receiver and  $\overline{\Theta}_k$  corresponds to the states where the TV channel cannot be played and it consists of system states with  $\omega = 0$  (states corresponding to equations (3.3) and (3.6)). The probability of watching the content and that of interruption are respectively given by:

$$P_E(\Theta_k) = \sum_{\{v=(\mathbf{a}, b, \omega=1)\}} \Pi(v) \quad (3.8)$$

$$P_E(\overline{\Theta}_k) = \sum_{\{v=(\mathbf{a}, b, \omega=0)\}} \Pi(v) \quad (3.9)$$

On the other side, the calculation of the service interruption frequency and duration are done in the same logic as the one depicted in sections 2.4.2 and 2.4.1 respectively, given the new system model (section 3.2.1) and the transition probabilities matrix defined in equations (3.3), (3.4), (3.5) and (3.6).

### 3.2.3 Numerical illustrations

To illustrate the impact of the playout buffer on the QoS metrics, we consider the same inputs used in the numerical analysis of the previous chapter, namely Section 2.5. We take  $TV_4$  as an example and we present the frequency and duration of interruption for different buffer sizes in Figure 3-2 and 3-3 respectively.

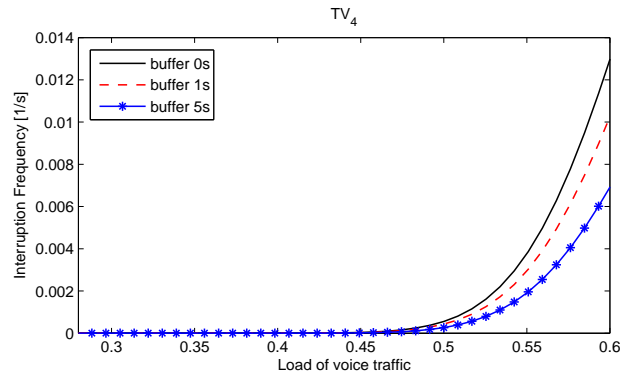


Figure 3-2: Frequency of interruption while watching  $TV_4$  for different buffer sizes

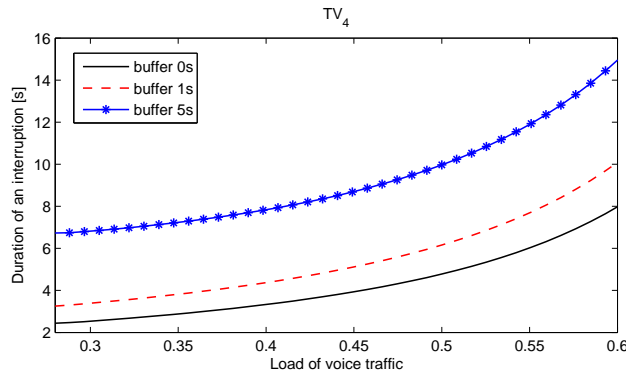


Figure 3-3: Duration of an interruption while watching  $TV_4$  for different buffer sizes

Figure 3-2 shows that for low voice traffic, the network is able to serve the TV channels without interruption and no buffer is needed in this case. The impact of the buffer appears at higher traffic levels and the interruption frequency decreases with the increasing buffer size. However, as shown in Figure 3-3, the duration of interruption increases with voice traffic intensity, and the buffer size has a negative impact on this

duration: Unlike the interruption frequency, the cut-off duration increases with buffer size, because of the buffering delay after each interruption.

These results could be used to dimension the LTE network without over-dimension it given the required QoS of TV service and the distribution of terminals types and therefore the receiver buffer size. For example if the majority of users have a terminal with buffer size of 5 [s], we consider the QoS results related to this buffer and proceed by the same planning process defined in Section 2.5 to determine the optimal LTE cell radius. They could be further used to define a dynamic buffer sizing scheme at the receiver side, in order to adapt the watching experience to the network state.

### 3.3 Case of lossy network

We consider in this section the case of a lossy channel where some transmitted content may be lost or arrives at destination with errors; the term channel referring to the radio propagation path and not the TV channel. We propose to take advantage of the presence of the playout buffer to ask for a retransmission at the application layer and recover these losses.

#### 3.3.1 Video frame loss probability

The service reliability in eMBMS is provided by two protection schemes: the Application Layer Forward Error Correction (AL FEC) and the Hybrid Automatic Repeat Request (HARQ). The former is a mandatory phase in the eMBMS session providing packet-level protection at the application layer, it specifically adds some redundant data bits, allowing thus the correction of corrupted data at the receiver side. The latter is an optional scheme and tightly related to the E-UTRAN Node B (eNB) capabilities and provides bit-level protection by repeating transmission on user requests.

On the other side, mobile TV content is sent with a rate of  $B$  [video frames/s]. Video frames must arrive each  $\frac{1}{B}$  [s] and any erroneous or delayed frame will be rejected. And so, the QoS is described by the video frame loss rate after FEC correction. Many works tried to assess these error probabilities [54–56] and we give in the following a simple explanation of the derivation procedure:

At the sender side, the video data is mapped onto  $N$  Source Blocks (SB) with a maximum size of 640 KB each and each SB is then divided into  $k$  source symbols with a maximum size of 512 B each [57]. The FEC encoder uses Raptor codes and generates for each  $k$  source symbols a given number of repair symbols. This latter, denoted by  $r$ , depends on the target error rate and the radio transmission conditions as well; for

instance a higher number of repair packets is needed in bad radio conditions with high BER [56], leading to higher AL FEC overhead [58]. These source and repair symbols are then mapped into FEC source and repair packets and finally into Protocol Data Units (PDU) at the MAC level and transmitted to the sender.

At the receiver side, a video frame is lost if at least one of its source blocks could not be decoded. The video frame loss probability, denote by  $P_{FL}$ , is thus given by:

$$P_{FL} = 1 - (1 - P_{SL})^N \quad (3.10)$$

With  $P_{SL}$  the source block packet loss after FEC decoding and  $N$  the number of source blocks a video frame is mapped to.

$P_{SL}$  is nothing but the probability of not being able to decode the considered source block (block of  $k$  source packets). In general, the Raptor code decoding failure probability depends on the number of received FEC symbols (whether source or repair) and is approximated by simulations in [59] as being:

$$p_f(m, k) = I_{\{m < k\}} + (0.85 \times 0.567^{m-k}) \cdot I_{\{m \geq k\}} \quad (3.11)$$

with  $k$  the original number of source symbols in the considered source block and  $m = u + v$  number of received symbols ( $u$  source symbols and  $v$  repair symbols).

Given that the conditional probability that a user is not able to decode the considered resource block given  $u$  is given by:

$$P(fail/u) = \sum_{v=0}^r \binom{r}{v} PER^{r-v} \times (1 - PER)^v \times p_f(v + u, k) \quad (3.12)$$

with  $PER$  the packet error rate at the radio level and  $PER^{r-v} \times (1 - PER)^v$  the probability of receiving  $v$  correct packets out of the  $r$  sent ones.

Finally, the source block loss probability,  $P_{SL}$ , is given by:

$$P_{SL} = \sum_{u=0}^k \binom{k}{u} PER^{k-u} \times (1 - PER)^u \times P(fail/u) \quad (3.13)$$

Given equations (3.10) and (3.13), we notice that a video frame will be lost with a probability that depends on the loss probability at the MAC layer  $PER$ . This latter probability is tightly related to the receiver radio conditions; namely the BER ( $PER = 1 - (BER^C)$  with  $C$  the number of bits in the packet). We note also that to have a target video frame loss probability  $P_{FL}$ , the eMBMS entity has to choose the optimal number of repair packets  $r$  that depends on  $PER$ .

However, as we are dealing with SFN transmission, adaptive modulation and coding cannot be used, and thus, the loss probability  $PER$  will change with the user position in the cell. A concrete example is given in [21], where authors proposed a method to model the BER in broadcast SFN networks, as a function of the received Signal to Noise Ratio (SNR) that depends itself on the user position in the cell.

Since the same signal is transmitted to all users, a trade-off between transmission redundancy and satisfied users is to be found [58]. This leads to the presence of a certain percentage of unsatisfied users where the protocol fails in recovering packet errors especially for user experiencing a very bad eMBMS channel. We hence propose here to introduce a complementary file repair mechanism at the application level to enhance the reliability of the transmission as follows: a receiver player that is not able to recover an erroneous video frame or does not receive a frame in an interval of  $\frac{1}{B}$  [s] will ask the video server for a retransmission. The latter will pop the requested video frame from its backup buffer and resend it if and only if it has enough resources to do so before the frame prior to the lost one is totally played. This retransmission differs from the HARQ that performs at the radio level.

We consider next a LTE cell divided into  $U$  concentric regions where users are equally distributed in the cell and denote the video frame loss probability experienced by a user at position  $u$  by  $p_u$ . We limit the attempt of each frame to one retransmission in order to limit the latency. We observe the system each  $\tau = \frac{1}{B}$  [s] and derive the probability of frame loss. This study is user dependent, as the buffer content is not the same for all users at each time instant, since some users may experience frame losses and others do not.

### 3.3.2 Impact of buffer on video frame loss probability

We previously defined the state of the buffer system as being the triple  $(\mathbf{a}, b, \omega)$  where  $\mathbf{a}$  is a  $S \times U$ -vector describing the number of  $S$  classes unicast flows present at each position  $u$  in the cell,  $b$  is the buffered duration and  $\omega$  is a boolean variable equal to 1 if the content is played and 0 otherwise (Section 3.2.1). Let us note that in this section, the buffer content of each user is different at each time instant, since some users may experience frame losses and others not.

As explained in section 3.2.1, the system states are partitioned into four ensembles: “Buffering Only States”:  $(\mathbf{a} \in \mathbf{A}_{\mathbf{k}}, 0 < b < D_b, \omega = 0)$ , “Buffering and Serving States”:  $(\mathbf{a} \in \mathbf{A}_{\mathbf{k}}, b > 0, \omega = 1)$ , “Service Only” States:  $(\mathbf{a} \in \overline{\mathbf{A}_{\mathbf{k}}}, b > 0, \omega = 1)$  and “Idle States”:  $(\forall \mathbf{a}, b = 0, \omega = 0)$ , where  $\mathbf{A}_{\mathbf{k}}$  is the subset of acceptable states when the LTE network can still serve the TV channel of priority  $k$  (Eqn. (2.18)),  $\overline{\mathbf{A}_{\mathbf{k}}}$  is its complementary subset (when the LTE network does not have sufficient resources to

deliver TV channel  $TV_k$ ) and  $D_b$  is the size of the buffer (maximal buffered content duration).

As stated in the beginning of this section, we propose to take advantage of the buffer to ask the base station for a unicast retransmission of a video frame if the latter is lost for a given user. As we are dealing with live TV transmission, the unicast retransmission of the lost frame should be done before the frames prior to the lost one are totally played. As a result of this constraint, the retransmission is only possible if the maximal buffer size  $D_b \geq \frac{2}{B}$  [s] and the buffer content is larger or equal to  $\frac{2}{B}$  [s] when the system transitions occur between "Buffering and Serving" states ( $B$  [video frames/s] is the transmission/playing rate of video frames). In fact, a video frame is discovered as erroneous (or lost) after  $\frac{1}{B}$  [s] and will be retransmitted in the next  $\frac{1}{B}$  [s] in parallel with a newly generated frame. We need, thus, a minimal of buffer size  $\frac{2}{B}$  [s] to store the retransmitted frame as well as the newly generated frame and a minimal buffer content of  $\frac{2}{B}$  [s] if the system is in "Buffering and Service" phase to conserve the continuity of frame playing. The parallel transmission of the newly generated frame via eMBMS bearer and the unicast retransmitted frame is possible, because by definition unicast and eMBMS services can be multiplexed within the same LTE frame. While their simultaneous reception depends on the receiver capabilities.

And so, the unicast retransmission of a lost video frame corresponding to TV channel  $TV_k$  for a user at position  $u$  is possible only if the latter constraints are met and if the remaining resources at the base station (PRB not used by unicast real-time services  $\mathbf{a}$ , broadcast TV channels ( $TV_i$  with  $i \in \{1, \dots, K\}$ ) and unicast retransmissions asked by other users watching higher priority TV channel(s)  $\{1, \dots, k-1\}$ ) are higher or equal to  $\frac{d_{TV}^{min}}{d_{RB}(u)}$ , with  $d_{TV}^{min}$  the minimal bitrate required by the considered TV channel and  $d_{RB}(u)$  the offered bitrate by a PRB for unicast services at position  $u$  (Sec. 2.2.2.1).

For the sake of illustration, given state  $(\mathbf{a}, b, \omega)$  at a considered time instant, we present in Figure 3-4 a possible profile of the buffer contents of a given user.

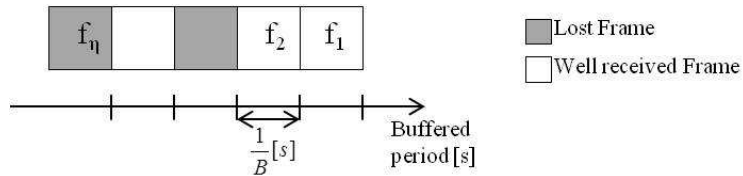


Figure 3-4: A given profile of buffer content

There are  $\eta = \frac{D_b}{\tau}$  time epochs, each  $\frac{1}{B}$  buffered seconds correspond to a frame that is either correctly received or lost/erroneous. Frame  $f_1$  is the one to be played at the next time step. So, the loss probability in this case is nothing but the sum of

state probabilities with  $f_1$  lost. A straightforward solution to get these probabilities is to extend the Markov chain defined in section 3.2.1 with  $\eta = \frac{D_b}{\tau}$  new variables representing the buffered frames (recall that  $D_b$  is the buffer size in units of time and  $\tau$  is the time step). But this would lead to a dramatic increase in the number of states of the Markov chain and would complicate computations. We hence propose another solution based on dynamic programming and the use of recursive equations. We define, for this purpose,  $P_j(\mathbf{a}, b, \omega)$  as the probability that the  $j^{th}$  buffered frame is lost/erroneous.

**Proposition 2**  $P_\eta(\mathbf{a}, b, \omega)$ , the loss probability of frame  $f_\eta$  of a given state  $(\mathbf{a}, b, \omega)$  is defined as follows:

- For a “Buffering only” state ( $\mathbf{a} \in \mathbf{A}_k, 0 < b < D_b, \omega = 0$ ):

$$P_\eta(\mathbf{a}, b, \omega) = \Pi(\mathbf{a}, b, \omega) \cdot \phi_p(\mathbf{a}) \quad (3.14)$$

And

$$\phi_p(\mathbf{a}) = \begin{cases} p_u & \text{if } D_b < \frac{2}{B} \\ \phi(\mathbf{a}) & \text{else} \end{cases} \quad (3.15)$$

with  $\Pi(\mathbf{a}, b, \omega)$  the stationary distribution of state  $(\mathbf{a}, b, \omega)$  (Eqn. (3.7)),  $p_u$  is the video frame error rate at cell position  $u$  (Eq. 3.10),  $B$  [video frame/s] is the transmission rate of video frame and  $\phi(\mathbf{a})$  the probability that the frame is lost and will not be retransmitted in the following time epoch (when the system state is  $\mathbf{a}$ ). We calculate  $\phi(\mathbf{a})$  it later in this section.

- For “Buffering and Serving” or “Service Only” states ( $\mathbf{a} \in \mathbf{A}, 0 < b \leq D_b, \omega = 1$ )

$$\begin{aligned} P_\eta(\mathbf{a}, b, \omega) = & \sum_{\mathbf{a}' \in \overline{\mathbf{A}_k}} P_{\eta+1}(\mathbf{a}', b + \tau, 1) Q_b((\mathbf{a}', b + \tau, 1), (\mathbf{a}, b, \omega)) \\ & + \sum_{\mathbf{a}' \in \mathbf{A}_k} \Pi(\mathbf{a}', b, 1) Q_b((\mathbf{a}, b, 1), (\mathbf{a}, b, \omega)) \phi'_p(\mathbf{a}) \\ & + \sum_{\mathbf{a}' \in \mathbf{A}_k} \Pi(\mathbf{a}', b - \tau, 0) Q_b((\mathbf{a}', b - \tau, 0), (\mathbf{a}, b, \omega)) \phi_p(\mathbf{a}) \end{aligned} \quad (3.16)$$

with  $P_{\eta+1}(\mathbf{a}', b + \tau, 1)$  the probability that the last frame  $\eta + 1$  (Fig. 3-4) is lost given a state with buffer duration  $b + \tau$  ( $\eta = \frac{b}{\tau}$ ) and  $\phi'_p(\mathbf{a})$  defined as follow.

$$\phi'_p(\mathbf{a}) = \begin{cases} p_u & \text{if } b < \frac{2}{B} \\ \phi_p(\mathbf{a}) & \text{else} \end{cases} \quad (3.17)$$

with  $\phi_p(\mathbf{a})$  the frame loss probability obtained by eq. (3.15).

The proof of this proposition is found in Appendix C.

**Proposition 3**  $P_j(\mathbf{a}, b, \omega)$ , the loss probabilities of frames  $f_j$  of a given state  $(\mathbf{a}, b, \omega)$  with  $j = \{1, \dots, \eta - 1\}$  are obtained recursively as follows:

- For a “Buffering only” state  $(\mathbf{a} \in \mathbf{A}_k, 0 < b < D_b, \omega = 0)$ :

$$P_j(\mathbf{a}, b, \omega) = \sum_{\forall \mathbf{a}' \in \mathbf{A}_k} P_j(\mathbf{a}', b - \tau, 0) \cdot Q_b((\mathbf{a}', b - \tau, 0), (\mathbf{a}, b, \omega)) \quad (3.18)$$

- For “Buffering and Serving” or “Service Only” states  $(\mathbf{a} \in \mathbf{A}, 0 < b \leq D_b, \omega = 1)$

$$\begin{aligned} P_j(\mathbf{a}, b, \omega) &= \sum_{\mathbf{a}' \in \overline{\mathbf{A}_k}} P_{j+1}(\mathbf{a}', b + \tau, 1) \cdot Q_b((\mathbf{a}', b + \tau, 1), (\mathbf{a}, b, \omega)) \\ &+ \sum_{\mathbf{a}' \in \mathbf{A}_k} P_{j+1}(\mathbf{a}', b, 1) \cdot Q_b((\mathbf{a}', b, 1), (\mathbf{a}, b, \omega)) \\ &+ \sum_{\mathbf{a}' \in \mathbf{A}_k} P_j(\mathbf{a}', b - \tau, 0) \cdot Q_b((\mathbf{a}', b - \tau, 0), (\mathbf{a}, b, \omega)) \end{aligned} \quad (3.19)$$

with  $\mathbf{A}$  the set of all acceptable unicast flows combinations (Eqn. (2.6)),  $\mathbf{A}_k$  the subset of those latter combinations where TV channel  $TV_k$  is served (Eqn. (2.18)) and  $\mathbf{Q}_b$  the transition matrix (Eqn. (3.3)).

The proof of this proposition is also given in Appendix C.

In order to calculate the previous probabilities, we need to calculate first  $\phi(\mathbf{a})$  the probability that the requested frame has been lost and will not be retransmitted in the following time epoch with a unicast real-time service state  $\mathbf{a}$ . The proof of the following proposition is given in Appendix D.

**Proposition 4**  $\phi(\mathbf{a})$  is given by:

$$\phi(\mathbf{a}) = p_u - \sum_{i=1}^{L_{\mathbf{X}_k}} s_{\mathbf{X}_k(i,:)} \cdot P_{\mathbf{X}_k(i,:)}^s(\mathbf{a}) \quad (3.20)$$

where  $p_u$  is the overall loss event probability perceived by the considered user at position  $u$ ,  $\mathbf{X}_k$  is a  $L_{\mathbf{X}_k} \times U$ -matrix, where  $\mathbf{X}_k(l, u)$  represents the number of potential unicast retransmission demands from  $TV_k$  users which are at position  $u$  (number of those users that have a lost frame),  $s_{\mathbf{X}_k(i,:)}$  is the probability that the demand of target user is among the  $\mathbf{X}_k(i, u)$  demands and  $P_{\mathbf{X}_k(i,:)}^s(\mathbf{a})$  is the probability of being able to serve  $\mathbf{X}_k(i, :)$  unicast retransmissions when we have the vector  $\mathbf{a}$  of served unicast services.



We propose, then, the following algorithm to compute all the defined probabilities:  
Algorithm 1:

1. Consider first the "Buffering Only" states ( $\mathbf{a} \in \mathbf{A}_k, 0 < b < D_b, \omega = 0$ )
2. Begin with  $b = \tau$ . Calculate the loss probability of frame  $f_\eta$  (Eqns. (3.14) and (3.16) for these states.
3. Move to "Buffering Only" states with  $b = b + \tau$  and calculate the loss probability  $P_j(\mathbf{a}, b, 0)$  of frame  $\{f_1, \dots, f_\eta\}$  in this order (Eqns. (3.18), (3.19), (3.14) and (3.16))  $\forall \mathbf{a} \in \mathbf{A}_k$ .
4. If  $b = D_b - \tau$  move to the next step else repeat step 3.
5. Consider next the "Buffering and service" and "Service only" states ( $\mathbf{a} \in \mathbf{A}, 0 < b \leq D_b, \omega = 1$ )
6. Begin with states with  $b = D_b$
7. Compute  $P_j(\mathbf{a}, b, 1)$  for  $j = \{\eta, \dots, 1\}$  (in this order)  $\forall \mathbf{a} \in \mathbf{A}$
8. If  $b = \tau$  stop else let  $b = b - \tau$  and return to step 7

At last, we can obtain the loss probability which is the sum of probabilities of serving states ( $\omega = 1$ ) having the first frame in the buffer lost:

$$P_{loss}^b = \sum_{\forall \mathbf{a} \forall b} P_1(\mathbf{a}, b, 1) \quad (3.21)$$

### 3.3.3 Impact of the re-transmission of lost frames on best-effort traffic

As explained in section 2.2.2.3, best-effort data traffic will consume the remaining PRBs after serving all the higher priority voice and TV services. And so in this case, we have to take also into account the resources consumed by the mobile TV unicast retransmissions. In this sense, the average resources offered for best-effort, which we denote by  $n_{RB_{BE}loss}$ , will depend on the number of these retransmissions and the already used parameters in Eq. (2.11) represented by the real-time connections  $\mathbf{a}$  and

the number of served TV channels  $k = n_{TV_{served}}(\mathbf{a})$  (Eq. (2.10)):

$$n_{RB_{BEloss}}(\mathbf{a}, \mathbf{R}_{\mathbf{a}}(l, :, :)) = \max \left[ N_{RB_{max}} - \sum_{i=1}^{|\mathbf{a}|} a_i \cdot n_{RB_i} - \sum_{j=1}^k \bar{n}_{RB}^{TV_j} - \sum_{u=1}^U \left( \sum_{j=1}^k \mathbf{R}_{\mathbf{a}}(l, u, j) \cdot \mathbf{Y}(u, j) \right), 0 \right] \quad (3.22)$$

where  $\mathbf{R}_{\mathbf{a}}$  is a  $L_{\mathbf{R}_{\mathbf{a}}} \times U \times k$  matrix with  $U$  the number of different error probability areas in the cell and  $k$  the number of served TV channels when the state of real-time unicast services is  $\mathbf{a}$ . Each vector  $\mathbf{R}_{\mathbf{a}}(l, u, :)$  corresponds to a given  $k$ -combination of the number of admissible retransmission demands of each TV channel  $j \in \{1, \dots, k\}$  for users at position  $u \in \{1, \dots, U\}$  whose minimal required bitrate, as well as that of  $k$  TV channels, can be guaranteed. With  $0 \leq \mathbf{R}_{\mathbf{a}}(l, u, j) \leq n_{TV_j}(u)$  and  $\sum_{u=1}^U \mathbf{R}_{\mathbf{a}}(l, u, j) \leq \sum_{u=1}^U n_{TV_j}(u)$  ( $n_{TV_j}(u)$  is the number of potential transmission demands belonging to  $TV_j$  at position  $u$  and is equal to the total number of these potential demands divided by  $U$ ). Finally  $\mathbf{Y}$  is a  $U \times k$ -matrix containing the average number of PRBs to be used by a unicast retransmission demand of TV channels of priorities 1 to  $k$  at each position  $u \in \{1, \dots, U\}$  in the cell (Eqn. (2.5) for  $d_s = \bar{d}_{TV}$ )

And so, the average number of remaining resources for best-effort data when the real-time unicast connection state is  $\mathbf{a}$  is given by:

$$\overline{n_{RB_{BEloss}}(\mathbf{a})} = \sum_{i=1}^{L_{\mathbf{R}_{\mathbf{a}}}} n_{RB_{loss}}^{BE}(\mathbf{a}, \mathbf{R}_{\mathbf{a}}(i, :, :)) \cdot Pr(\mathbf{R}_{\mathbf{a}}(i, :, :)) \quad (3.23)$$

where  $Pr(\mathbf{R}_{\mathbf{a}}(i, :, :))$  is the probability of having the combination of retransmission demands from the  $k$  TV channels users at all positions  $u$  of the cell and is calculated as follows:

$$Pr(\mathbf{R}_{\mathbf{a}}(i, :, :)) = \prod_{u=1}^U \prod_{j=1}^k \binom{n_{TV_j}(u)}{\mathbf{R}_{\mathbf{a}}(i, u, j)} p_u^{\mathbf{R}_{\mathbf{a}}(i, u, j)} (1 - p_u)^{n_{TV_j}(u) - \mathbf{R}_{\mathbf{a}}(i, u, j)} \quad (3.24)$$

And then we use the same PS equations (2.12), (2.13) and (2.16), to calculate the average offered throughput for a best-effort data user.

### 3.3.4 Numerical illustrations

We illustrate the case of a lossy channel with a loss probability  $p_c = 0.05$  in the center area and  $p_o = 0.15$  in the outer one. We consider 7 target TV channels of

512 Kbps each and a number of TV users equal to 50 users partitioned according to TV priorities as follows: ( $n_{TV_1} = 19, n_{TV_2} = 12, n_{TV_3} = 9, n_{TV_4} = 5, n_{TV_5} = 2, n_{TV_6} = 2, n_{TV_7} = 1$ ) and equally distributed between cell areas. The number of TV channels is an important input in this section because of the unicast retransmission demands; every single demand will affect the network performance.

We show in Figures 3-5-a and 3-5-b the loss probability of the highest priority TV channel  $TV_1$  for different buffer sizes for users at the center and outer regions.

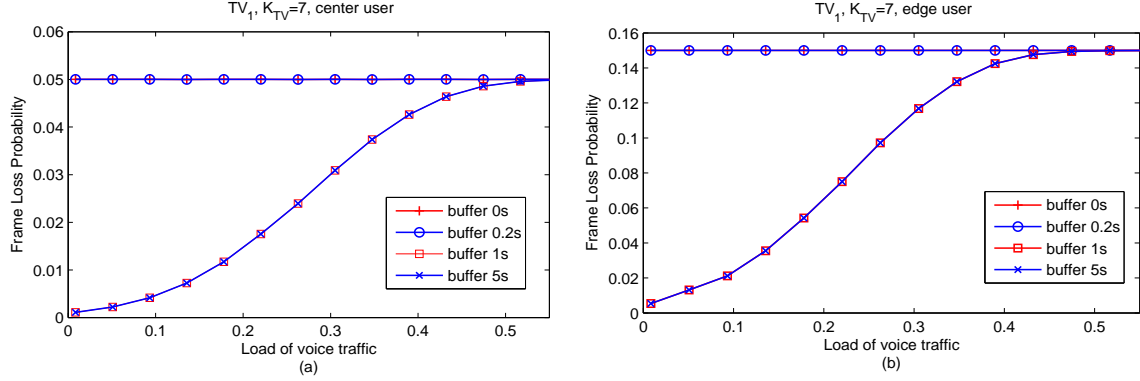


Figure 3-5: Loss probability of the highest order TV channel for different buffer sizes

We note that for the case with a buffer size less than  $\frac{2}{B}$  with  $B$  [frame/s] is the video frame transmission rate (in the figure for buffer size 0.2 [s]), the loss probability is nothing but  $p_u \times P(\Theta_k)$  where  $P(\Theta_k)$  is the probability of serving the TV channel (it is equal to  $1 - P(\overline{\Theta_k})$ ;  $P(\overline{\Theta_k})$  is shown in Fig. 2-6). The introduction of a buffer at the receiver with a size  $\geq \frac{2}{B}$  (in the figure 1 and 5 [s]) will lead to an enhancement in the loss probability for low voice traffic, because in this traffic region we can still find non used resource blocks and use them for retransmission. We notice that those buffer sizes has no impact here, because we limit the retransmission attempt to only one retransmission whatever is the buffer size.

We plot in Figure 3-6 the percentage in the loss probability enhancement after the introduction of a buffer for center and edge region users. We consider two different priority channels  $TV_1$  and  $TV_4$ . Results show that the percentage of enhancement is lower for users experiencing bad reception conditions, because given their high loss probability, the base station will not always have the opportunity to recover these losses.

It is important to see the impact of the number of broadcast TV channels on this loss probability, and so we consider a cell edge user ( $p_u = 0.15$ ) and present in Figure 3-7 the enhancement in the loss probability for the highest priority TV channel  $TV_1$  and a lesser priority one  $TV_4$  for two cases: number of broadcast TV channels

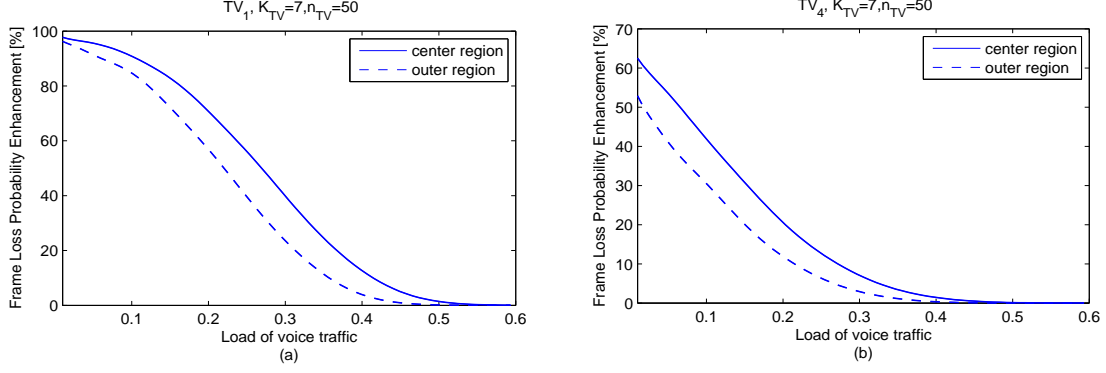


Figure 3-6: Enhancement in the loss probability for a center and edge TV channel user

$K_{TV} = 7$  and  $K_{TV} = 4$ .

Indeed the number of broadcast TV channels affects the loss probability experienced by a user: for example the enhancement in loss probability felt by TV<sub>1</sub> user is up to 100% in case when we have only 4 TV channels to be broadcast and it is 95.5% when the number of broadcast TV channels increases to 7. The same remark holds for the less priority TV channel TV<sub>4</sub> (enhancement up to 90.52% for 4 broadcast TV channels and 50.31% for the other case). This is due to the fact that the overall number of TV channels will be always broadcast and will consume a large part of the network resources and we cannot always find sufficient resources to serve the unicast retransmission demands.

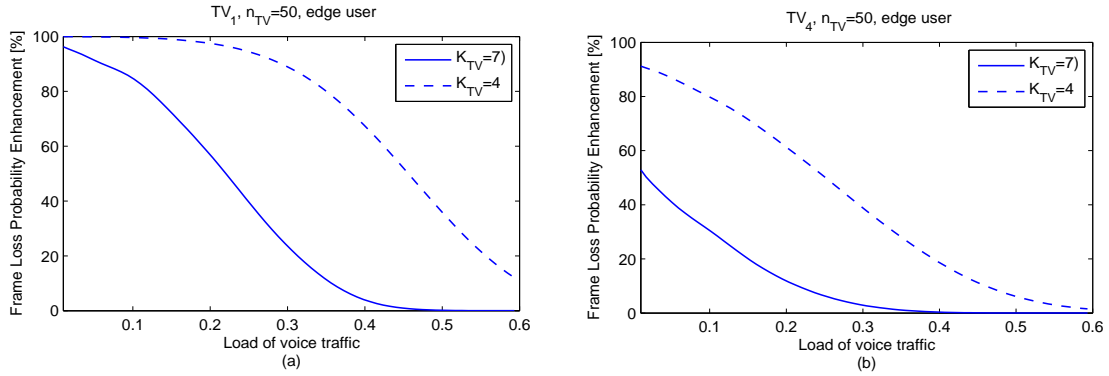


Figure 3-7: Loss probability of an edge user for two different priority TV channels and different number of broadcast TV channels

We note also by comparing Figures 3-7-a and 3-7-b that the high priority TV channel users will benefit more from the buffer since their unicast retransmission demands are prioritized over those of lower priority TV channel users, when there are no sufficient resources to serve both.

We present further in Figure 3-8 the impact of the loss probability enhancement for a cell edge user ( $P_u = 0.15$ ) of  $TV_1$  and another of  $TV_4$  when we have 7 TV channels to be broadcast. We consider two cases: a first one with a number of mobile TV users  $n_{TV} = 50$  partitioned as follows: ( $n_{TV_1} = 19, n_{TV_2} = 12, n_{TV_3} = 9, n_{TV_4} = 5, n_{TV_5} = 2, n_{TV_6} = 2, n_{TV_7} = 1$ ) and a second one with  $n_{TV} = 24$  ( $(n_{TV_1} = 9, n_{TV_2} = 4, n_{TV_3} = 3, n_{TV_4} = 3, n_{TV_5} = 2, n_{TV_6} = 1, n_{TV_7} = 1)$ ).

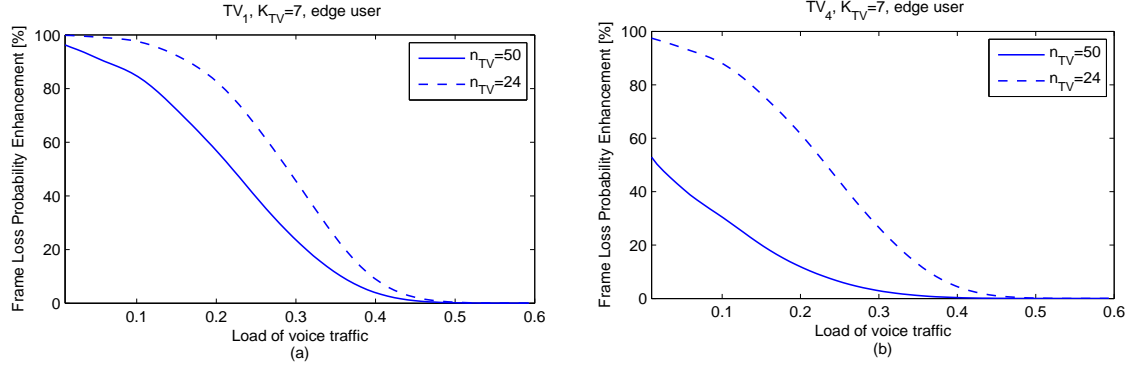


Figure 3-8: Loss Probability of an edge user for two different priority TV channels and different number of TV users

Our results show that the presence of the playout buffer leads to a higher enhancement in the case when the number of TV users is smaller.

Finally, to illustrate the impact of the re-transmission on best effort traffic, we consider a data traffic intensity of 250 [Kbps/cell] and show in figure 3-9 the effect of the number of TV users on the best-effort data performance when we have 4 TV channels and two loss probability areas  $p_{center} = 0.05$  and  $p_{outer} = 0.15$ .

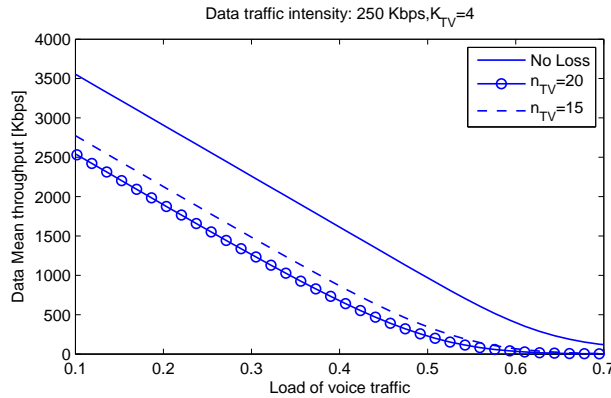


Figure 3-9: Average data throughput for different number of TV users in a lossy system with  $p_{center} = 0.05$  and  $p_{outer} = 0.15$

We notice that the data throughput decreases with the number of TV users since the average number of consumed resources by those users increases.

### 3.4 Conclusion

To sum up, we extend in this chapter the QoS study done in chapter 2 by investigating the impact of the receiver playout buffer on the performance of mobile TV reception.

We showed that the buffer helps decreasing the number of interruptions during the TV session at the expense of an increase of its duration. As a consequence, a large buffer size is to be used when the interruption frequency is considered as more annoying than its duration. When the duration of the interruption is to be reduced, a smaller buffer is to be used. Results can be used by engineers to define a dynamic buffer management and hence enhance the user QoS or to plan the LTE network without over-dimensioning it, taking into account the TV required performance and the majority of user terminals (majority of receiver buffer size).

We next investigated the opportunity of using the buffer for recovering from frame losses using unicast retransmission. We proposed a unicast file repair mechanism at the application layer and we derived recursive closed-form equations for the resulting loss probability. Our results showed that buffering is useful for combating losses only when voice traffic is low and for a low number of TV channels and TV users. Otherwise, the network will not have sufficient resources for retransmission and the impact of retransmission on best-effort data performance is negative.

This chapter is the last key in the so-called planning part of the our thesis, where we proposed a realistic design of cooperative DVB/LTE network offering mobile TV services. The economical and business model issues raised in such a hybrid network are examined in the following part of the thesis document.

## Part II

# Hybrid DVB/LTE network for Mobile TV delivery: Economical Considerations

## Chapter 4

# Profit sharing in hybrid LTE/DVB systems

The success of a cooperative network is influenced by technical constraints as well as by economical ones. In fact, the main problem that encountered the DVB-H/UMTS cooperation was the failure to find acceptable business models between agents collaborating for a common delivery of mobile TV.

The nature of such cooperative cases between players with common earned profits and conflicting interests, poses two major economic difficulties: finding the best coalition between all possible ones and the optimal profit distribution strategy. Given that, we aim in this chapter to define a collaborative business model that treats fairly all agents contributing to the considered service delivery.

In this direction, we introduce first the Mobile TV value chain. We investigate then some related works on the economic aspects in broadcast/cellular networks. We propose next a profit sharing strategy, in terms of revenues and costs, between the different players, using coalition game concept Shapley value [12], and the optimal coalition of the players, at the Nash equilibrium [13].

### 4.1 Mobile TV value chain

The first step in any economical study is the identification of the key players and their activities defining what we call the service value chain.

Many papers tried to explore the ecosystem of delivering the Mobile TV end service to the consumer [60–62]. We noticed that mobile TV offers real business opportunities for multiple actors from the telecommunication sector and from outside it creating emerging value chain as the one depicted in Figure 4-1.



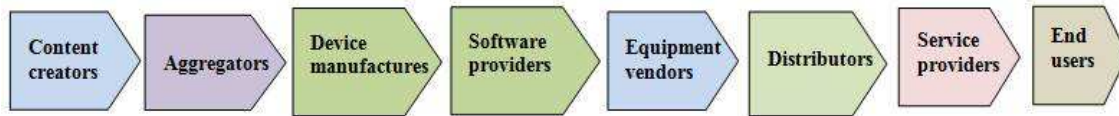


Figure 4-1: The value chain of mobile TV

1. *Content creators*: These include the creators of mobile TV contents that could be different from the traditional TV programs or at least adjusted and modified to fit customers need and device. In [60] two kinds of content were distinguished: The first consists of the pure rebroadcasting of the traditional TV program, while the second consists of developing a complete new TV program specially designed for the reception by a mobile handset. This would include the reformatting of existing content as well as the creation of completely new content. Examples of content creators are artistic production companies.
2. *Aggregators*: These actors select and package content from different sources (content creators) into convenient and attractive bundles. They distribute the content through various channels depending on their distribution rights as defined in [60]. Note that aggregators can create a part of the content they offer playing thus the double role of content creator and aggregator. Examples of possible aggregators are the following:
  - Pay TV companies like Canal+ in France that offer their own bundles to clients through broadcasting networks
  - TV broadcasters that play already the role of content aggregator in the classical TV landscape and could also perform this activity in the mobile TV value chain ([63], p. 141).
  - Mobile Network Operators (MNO) may have their own bundles of TV chains and play thus the role of content aggregator
  - Even equipment vendors such as Ericsson and Nokia may be willing to expand their core competencies by entering the value chain activity of content aggregation (e.g., Preminet service offered by Nokia to operators with download and billing framework [64]).
  - From the Internet world, there exists strong opportunities for actors from the value chain of entertainment and media companies like Google, Amazon, Netflix, and Microsoft for playing the role of aggregator.

To sum up, various actors can play the role of aggregator, both from the traditional media sector and from the mobile sector.

3. *Device manufactures*: Mobile TV devices may be the same as those used for cellular networks (mobile phones, smartphones, tablets) or may be specific to the TV service (e.g. via a dongle or a specific device), depending on the deployment scenario. Traditional device manufacturers (Apple, Samsung, Nokia, etc) are expected to be the main actors here.
4. *Software providers*: An important actor in the value chain is the provider of software enablers, including video players and TV portals. While the design of TV portals can be performed by any software developing company, the player market is dominated by large software companies like Microsoft and Google.
5. *Equipment vendors*: Mobile TV broadcast equipment providers vary following the network technology. While traditional broadcast providers (e.g. Thomson) will be prevalent in DVB-based networks, mobile telecommunication equipment vendors (Ericsson, Huawei, NSN, etc.) will provide eMBMS broadcast capabilities integrated to their 4G base stations.
6. *Distributors*: offer their TV programs and content to customers via broadcasting networks that they deploy and operate using software enablers. We consider the following three cases depending over which kind of network the delivering content is done
  - (a) MNOs over their cellular networks, using the unicast technology (too costly) or the broadcast one (LTE eMBMS) [32]. In this case, MNOs may use the broadcasters network in order to enhance the coverage (as a supplier).
  - (b) An actor using mainly a DVB network (DVB-T2 Lite or DVB-NGH), with or without help of cellular networks for coverage extension and service repair [21]. This actor may be an alliance between an aggregator and a TV broadcaster
  - (c) A joint venture between a mobile network operator and an aggregator/broadcaster alliance
7. *Service providers*: Service providers are the companies that offer wireless services to end clients. Their services include:
  - Mobile TV services

- Voice calls local, regional, national, and international
- Voice services like voice mail, caller ID, call waiting, call forwarding
- Data services like SMS messages, Text Alerts, Web browsing, e-mailing, streaming, etc

We note that, in most of the cases, network operators are still playing the role of service providers.

8. *End users*: The value chain ends with customers (individual users, companies, administrations) who adopt to wireless products and services offered by service providers. End-users, although acting independently through their own actions, are influenced by each others actions and create increasing returns by creating a critical mass that accelerates adoption of service.

## 4.2 Literature review

Very few works addressed economical issues in convergent DVB/cellular networks. Most of the studies focused on the definition of mobile TV business model roles [65–67]. In fact, the role of the previously introduced key stakeholders in the mobile TV delivery varies from market to market. It depends on many factors including the core competencies of each actor, its resources, relationships, its ability to partner within the value chain actors and its ability to establish a customer base. In the same logic, if an actor could have multiple positions in this new value chain, it has to make an adequate choice among these possible positions taking into account the Market constraints. Understanding the actor position in the emerging value chain is thus primordial for elaborating a strategy, the latter being traditionally seen as "the art of positioning a company in the right place on the value chain" [68]. Authors in [65] tried to identify the emerging cooperation models between the various stakeholders piloting mobile broadcasting in Europe, based on the analysis of different technological trials. Authors in [66, 67] proposed some potential business model implementations: a market led by mobile network operator, an other led by pay TV/broadcast alliance and a cooperative mobile/broadcast operators market. These analysis were however solely qualitative with no quantitative results.

Other works [69] considered cooperative broadcast and mobile telecommunication networks. They assessed the efficiency of the management of the convergent network and derived policies that increase the network profitability. They however did so in a centralized way, as if both operators acted as one.

### 4.3 Proposed model

Building on the qualitative analysis developed above, this section presents a quantitative analysis for a hybrid DVB/LTE mobile TV network. We begin by a technical-economic analysis of revenues and costs in our mobile TV broadcasting network before deriving the profit of each of the key actors in this network; namely the DVB and LTE operators as well as the TV providers. We derive closed-form expressions for each player profit share using coalition game concept Shapley value, which proved to be very effective in profit sharing in a multi-player context where several types of relationships, bilateral and multi-lateral, are involved [70]. The idea is that each player will have a profit share proportional to its contribution in the network setting and the added value it brings to the overall value chain.

We consider two cases: one in which both LTE and DVB networks are managed by a single operator and one in which the operators are separate. The results of this section are general and can be applied with suitable modifications to fit potential market implementations.

#### 4.3.1 Revenues and cost analysis of the Mobile TV network

##### Revenues

In general mobile TV service is offered in form of various channel bouquets with a given subscription fee per user. This latter is larger when the content is richer. Standalone cellular and broadcast operators can offer different TV channels, and by their cooperation the user will be able to receive both cellular and DVB TV bouquets.

However, the client databases of the cellular of size  $X_L$ , and the broadcast operators of size  $X_D$ , could have a certain number of common customers (that have for instance a mobile subscription to the MNO and a fixed TV subscription to the broadcast bouquets), denoted by  $X_{com}$ , so that competition would reduce the number of subscribers to each of the networks (compared to the stand alone case). So, in case of competitive networks and assuming that the common users are evenly divided among networks, the number of mobile TV subscribers becomes:

$$\begin{aligned} X'_L &= X_L - \frac{X_{com}}{2} \\ X'_D &= X_D - \frac{X_{com}}{2} \end{aligned} \tag{4.1}$$

On the other hand, cooperation will not result in a simple summation of the customer databases sizes but it will lead instead to an overall number of subscribers

given by:

$$X_{coop} = X_L + X_D - X_{com} \quad (4.2)$$

## DVB costs

The main sources of costs in a DVB network in general and that offering Mobile TV in particular, include both the required infrastructure and operational costs. However, as we previously said, DVB operators tend to use their already existent infrastructures providing rooftop fixed TV service, to deliver in-band mobile TV. As a result, the infrastructure costs of this mobile TV network are dropped from the costs analysis and only the operational costs will be taken into account.

The main network operation cost is, thus, the energy cost, governed by the power transmitted by the DVB tower. This power is determined based on the capacity and coverage requirements as depicted in Figure 4-2:

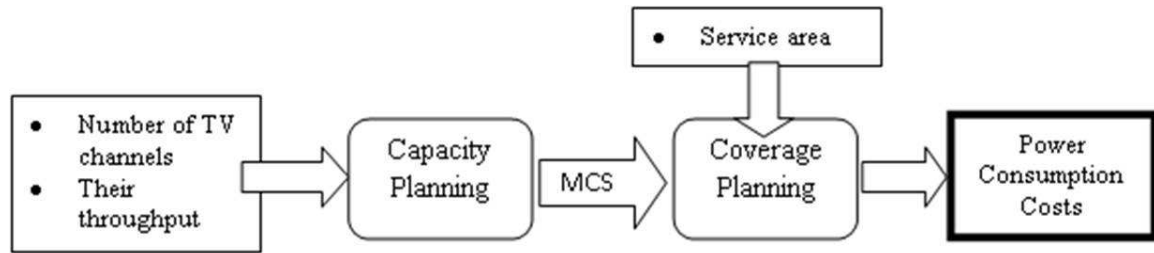


Figure 4-2: DVB Costs derivation

The DVB operator has a capacity objective that is expressed in the number of channels it has to serve and the type of receiver it targets (for example some channels may deliver High Definition (HD) resolutions and others Single Definition (SD) ones). The aggregated throughput required by the channels is thus the sum of the required throughput of each of them. As the spectrum allocated to the DVB operator is limited, when this aggregated throughput is higher, the operator has to use more efficiently its spectral resources. This step is the capacity planning process (section 2.1.2.2) that consists in choosing the Modulation and Coding Scheme (MCS) that allows satisfying the throughput targets. Examples of the number of channels that can be served for the different MCS has been given in Table 2.2.

This capacity boosting by using a higher MCS comes at a cost. In fact, a larger modulation is less robust to noise and requires a higher transmission power if the aim is to reach receivers that are far from the transmitter. As the objective of DVB operators is to reuse the same infrastructure as the terrestrial DVB, the latter distance is imposed and the only option for the DVB operator is to increase its transmission

power. This is called the coverage planning (section 2.1.2.1) and has been illustrated in figure 2-2 that gives, for each MCS, the required transmission power for covering a given radius.

To summarize the process, the chosen MCS depends on the set of TV channels, denoted by  $\mathbf{K}_{\mathbf{TV}}$ , and the transmitted power depends on the later chosen MCS and the DVB cell radius, noted by  $R_D$ .

On the other side, the transmitter consumed power  $P_c(R_D, \mathbf{K}_{\mathbf{TV}})$  is higher than the radiated power (ERP) and includes a component that is proportional to the ERP and another one that is consumed independently of the average transmit power [71]:

$$P_c(R_D, \mathbf{K}_{\mathbf{TV}}) = \alpha_n P_D(R_D, MCS(\mathbf{K}_{\mathbf{TV}})) + \beta_n \quad (4.3)$$

where  $P_D(R_D, MCS(\mathbf{K}_{\mathbf{TV}}))$  is the radiated power,  $\alpha_n$  is a scaling coefficient due to amplifier and feeder losses as well as cooling of sites and  $\beta_n$  is an offset due to signal processing, battery backup, etc.

Eventually, the total monthly cost of one DVB transmitter covering a region of radius  $R_D$  and serving the set of TV channels  $\mathbf{K}_{\mathbf{TV}}$  in a hybrid LTE/DVB network is composed of power consumption costs and equipment costs  $C_D^{rent}$  [72] and is given by:

$$C_D(R_D, \mathbf{K}_{\mathbf{TV}}) = \alpha_e P_c(R_D, \mathbf{K}_{\mathbf{TV}}) \cdot H + C_D^{rent} \quad (4.4)$$

where  $\alpha_e$  is the electricity cost of one kWh and  $H$  is the number of operating hours per month.

It is clear that the largest is the radius of the area to be covered by the DVB tower, the highest is the transmitted power and the highest is the cost.

## LTE costs

LTE operators has to offer Mobile TV without altering the blocking probability of the real-time unicast services and the average offered throughput of data ones. Those metrics depend tightly on the resources allocated for the considered services (sections 2.2.2.1 and 2.2.2.3). If the voice and data traffic volume is low, there will be space for offering the mobile TV service over the same 3G+ infrastructure, otherwise, it will be necessary to densify the network by deploying more base station sites, since the unicast and broadcast offered capacities increase when the LTE cell radius decreases (figure 2-4 and table 2.4).

For a memory refresh we re-describe in the following the steps to update an existing LTE network of cell radius  $R_0$  and targeting the service of the set  $\mathbf{K}_{\mathbf{TV}}$  of TV channels. We consider that this network was primarily serving an area of

radius  $R_S$  offering voice services with an average traffic intensity of  $E$  [Erlang/Km<sup>2</sup>] and a target blocking probability  $B_0$  as well as data service with a minimum target throughput  $D_0$  and intensity  $A_0$ .

1. Begin with the existing network with no TV (noted baseline network) with a cell radius  $R_L = \hat{R}_L(0)$  and an overall number of available PRBs:  $N_{RB}^{max}$ .
2. Derive the QoS metrics as section 2.4 to determine the maximal voice traffic intensity,  $E_{max}$ , that can be served in the considered LTE cell.
3. If  $\frac{E_{max}}{\pi \cdot (\hat{R}_L(0))^2} \geq E$  and the voice and data services QoS meet the maximal blocking probability  $B_0$  and minimal data user throughput  $D_0$ , the considered cell radius is optimal and we denoted by  $\hat{R}_L(\mathbf{K}_{TV})$ . Otherwise, a higher capacity is needed, and thus the LTE cell radius is decreased and we repeat steps 2-3.

Once we obtain the optimal cell radius, we calculate the additional number of LTE sites needed to serve mobile TV service. Referring to Figure 2-5, there are two LTE regions: in the inner region, DVB is able to serve all users and the LTE operator does not need to upgrade its network. The outer region, of area  $\pi(R_S^2 - R_D^2)$ , is however not covered by DVB, and so LTE has to upgrade its network so as to serve mobile TV users. The number of LTE sites to be added, per DVB transmitter, in this region is given by:

$$\Delta_L(R_D, \mathbf{K}_{TV}) = \pi(R_S^2 - R_D^2) \left( \frac{1}{S_L(\hat{R}_L(\mathbf{K}_{TV}))} - \frac{1}{S_L(\hat{R}_L(0))} \right) \quad (4.5)$$

where  $S_L(R_L(\mathbf{K}_{TV})) = \pi \cdot (R_L(\mathbf{K}_{TV}))^2$  is the LTE cell surface for cell radius  $R_L(\mathbf{K}_{TV})$  when the set of TV channels to be served is  $\mathbf{K}_{TV}$ .

The monthly LTE network upgrading cost is thus obtained by:

$$C_L(R_D, \mathbf{K}_{TV}) = \alpha_L \Delta_L(R_D, \mathbf{K}_{TV}) \quad (4.6)$$

where  $\alpha_L$  is the monthly cost of a new LTE site, including operational cost as well as equipment and installation costs.

### 4.3.2 The Shapley Value: definition and properties

The Shapley value, defined by [12], is a fair solution to distribute a common payoff in multi-player environments. It presents *the value that assigns an expected marginal contribution to each player in the game with respect to a uniform distribution over the set of all permutations on the set of players* [73]. In this direction, we denote by

$N$  the set of players and  $S$  a given coalition formed by a subset of these players. The worth function  $V(S)$  denotes the weight or payoff of coalition  $S$ . The Shapley value,  $\phi_i(S, V)$ , is the share gained by player  $i$  when it is in coalition  $S$  and is given by:

$$\phi_i(S, V) = \frac{1}{N!} \sum_{\pi \in \Pi} \Delta_i(V, S(\pi, i)) \forall i \in N \quad (4.7)$$

where  $\Pi$  is the set of all  $N!$  players permutation,  $S(\pi, i)$  is the coalition formed by players from rank 1 till  $i$  in a given permutation  $\pi \in \Pi$  and  $\Delta_i(V, S(\pi, i)) = V(S) - V(S \setminus \{i\})$  is the marginal contribution of player  $i$  in coalition  $S$ , defined as the difference between the worth functions of  $(S)$  and  $(S \setminus \{i\})$ , and representing the benefits or losses that player  $i$  could bring if he entered coalition  $(S \setminus \{i\})$ .

### Properties:

The Shapley value has the following properties:

- a. Additivity: If the worth function  $V(S)$  can be divided into two components  $V(S) = V_1(S) + V_2(S)$ , then the Shapley value verifies  $\phi_i(S, V) = \phi_i(S, V_1) + \phi_i(S, V_2)$
- b. Efficiency: There is a conservation of the total value of the coalition:

$$\sum_{i \in S} \phi_i(S, V) = V(S) \quad (4.8)$$

- c. Balance contribution: For any two players  $i$  and  $j$ , the Shapley values are balanced as follows:

$$\phi_i(S, V) - \phi_i(S \setminus \{j\}, V) = \phi_j(S, V) - \phi_j(S \setminus \{i\}, V) \quad (4.9)$$

### Stability

The Shapley distribution is stable if it is in the core of the game. The latter is defined in [74] as "the set of feasible payoff vectors for the grand coalition that no coalition can upset". So the Shapley value profit sharing is stable if we cannot find any coalition whose players may earn more than if they stick to the largest coalition (the grand coalition). Formally, it should verify the following condition:

$$\sum_{(i \in S)} \phi_i(P', V') \geq V'(S) \quad \forall S \subseteq P' \quad (4.10)$$



### 4.3.3 Profit sharing strategy: Case of joint LTE/DVB operator

We consider in this section a hybrid LTE/DVB system owned and managed by a single operator. In this case, profit sharing is between the operator and the TV channel providers. We denote the set of players  $P_o$  by the *grand coalition* composed of the operator and a set  $\mathbf{K}_{\text{TV}}$  of  $K = |\mathbf{K}_{\text{TV}}|$  TV channel providers. We consider that each TV channel provider sells one TV channel. Let  $N$  denote the number of players in the set  $P_o$ :  $N = |P_o| = K + 1$ .

The profit is the difference between the total revenue and costs, and is to be shared among the different players in the system. Using the above-defined additivity property (Section 4.3.2), the worth function of any coalition  $S$ , i.e., its payoff  $V(S)$ , is simply the difference of the revenue worth function  $V_r(S)$  and the cost worth function  $V_c(S)$ . This yields the profit share of each player  $i$  as follows:

$$\phi_i(S, V) = \phi_i^r(S, V_r) - \phi_i^c(S, V_c) \quad (4.11)$$

$r$  is the revenue component and  $c$  is the cost. We consider a single DVB tower. The profits are thus given per service area and can be scaled to obtain the overall profits.

We now derive closed-form expressions for the Shapley value so as to ease its numerical computation and overcome the exhaustive summation in Eqn. (4.7).

#### 4.3.3.1 Revenue Sharing

Revenue depends on the pricing model and the willingness of customers to subscribe to given channel(s). As we previously said, operators offer, in general, various channel bouquets with a flat rate for each one. But, by observing the popularity of each channel, operators can estimate the individual revenue generated by each channel apart. Let  $\delta$  be the subscription fee per user to a certain bouquet and let  $X$  be the number of subscriptions to it.  $\delta_i = p(i)\delta \cdot X$  is the subscription fee paid by mobile TV user to channel  $i$  with popularity  $p(i)$  in this bouquet.

Given that the revenue worth function is defined as follows:

$$V_r(S) = \left[ \sum_{i \in S} \delta_i \right] I_{\{\text{operator} \in (S)\}} \quad (4.12)$$

where  $I_B = 1$  if condition  $B$  is true and 0 otherwise.

By additivity, this function can be also re-written as:  $V_r(S) = \sum_i V_r^i(S)$  where:

$$V_r^i(S) = \delta_i I_{\{\text{operator and } i \in (S)\}} \quad (4.13)$$

This simplifies the computation. For each  $(S, V_r^i)$ , we eliminate channels  $j, \forall j \neq i$ , as these channels are dummy players for this worth function [12]. The revenue sharing is then easily obtained by applying Eqn. (4.7) to the remaining two players (*operator* and channel  $i$ ) given the worth function  $V_r^i$ . We obtain thus the operator's revenue share  $\phi_o^r(S, V_r^i) = \frac{\delta_i}{2}$  and the share of channel  $i$ ,  $\phi_i^r(S, V_r^i) = \frac{\delta_i}{2}$ . Finally, as the operator is serving a set  $\mathbf{K}_{\mathbf{TV}}$  of TV channels, its revenue share is the sum of its share in every channel revenue and is given by Eqn. (4.14). The revenue share of the TV channel provider  $i$  is given by Eqn. (4.15)<sup>1</sup>:

$$\phi_o^r(R_D, P_o, V_r) = \frac{\sum_i^{|\mathbf{K}_{\mathbf{TV}}|} \delta_i}{2} \quad (4.14)$$

$$\phi_i^r(R_D, P_o, V_r) = \frac{\delta_i}{2} \quad (4.15)$$

#### 4.3.3.2 Cost Sharing

As we consider, in this section, that a single operator runs the hybrid network, the total operator cost includes DVB (Eqn. (4.4)) as well as LTE (Eqn. (4.6)) costs. The cost worth function is:

$$V_c(R_D, S) = [C_D(R_D, \mathbf{k}_{\mathbf{TV}}) + C_L(R_D, \mathbf{k}_{\mathbf{TV}}) + \sum_{i=1/i \in (S)}^{|\mathbf{K}_{\mathbf{TV}}|} c_i] I_{\{operator \in (S)\}} \quad (4.16)$$

where  $\mathbf{k}_{\mathbf{TV}}$  is the subset of TV channels in coalition  $S$ ,  $\mathbf{K}_{\mathbf{TV}}$  is the total set of TV channels and  $c_i$  is channel  $i$  contents cost.

The previous worth function could be divided into four components: the power cost worth function  $V_c^P(R_D, S) = \alpha_e \cdot H \cdot P_D(R_D, \mathbf{k}_{\mathbf{TV}}) I_{\{operator \in (S)\}}$ , the broadcast equipment cost worth function  $V_c^{rent}(R_D, S) = C_D^{rent} I_{\{operator \in (S)\}}$  due to needed updates of antennas, cooling system and other communication material needed to support the Mobile TV service, the infrastructure cost worth function in number of additional LTE base stations  $V_c^{bs}(R_D, S) = C_L(R_D, \mathbf{k}_{\mathbf{TV}}) I_{\{operator \in (S)\}}$ , and finally, the content cost worth function  $V_c^{content}(R_D, S) = (\sum_{i=1/i \in (S)}^{|\mathbf{K}_{\mathbf{TV}}|} c_i) I_{\{operator \in (S)\}}$  due to production costs or for buying contents from other production companies other than the operator. Using the Shapley definition (Eqn. (4.7)), we obtain the expressions for the four components of cost share of the operator (see Appendix E):

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<sup>1</sup>If a TV channel provider sells a set  $L$  of more than one TV channel, its revenue share is the sum of the revenue share obtained by each channel in  $L$  given by Eqn. 4.15

i. The operator power cost share is given by:

$$\phi_o^P(R_D, P_o, V_c^P) = \alpha_e \cdot H \frac{\sum_{i=2}^N (i-1)! \left( \sum_{j=1}^{m_{i-1}} P_c(R_D, (\mathbf{e}_{i-1})_{j*}) \right) (N-i)!}{N!} \quad (4.17)$$

ii. The operator cellular infrastructure cost share is equal to:

$$\phi_o^{bs}(R_D, P_o, V_c^{bs}) = \frac{\sum_{i=2}^N (i-1)! \left( \sum_{j=1}^{m_{i-1}} C_L(R_D, (\mathbf{e}_{i-1})_{j*}) \right) (N-i)!}{N!} \quad (4.18)$$

where:

- $N$  is the total number of players ( $N = |\mathbf{K}_{\mathbf{TV}}| + 1$ ),
- $\mathbf{e}_{i-1}$  is a  $(m_{i-1} \times |\mathbf{K}_{\mathbf{TV}}|)$  matrix. Each column  $k$  in this matrix corresponds to the channel  $k$  in the set  $\mathbf{K}_{\mathbf{TV}}$ . The number of its lines is  $m_{i-1} = \binom{|\mathbf{K}_{\mathbf{TV}}|}{i-1}$ . Each  $j^{th}$  line  $(\mathbf{e}_{i-1})_{j*}$  in this matrix represents a different combination of  $i-1$  served TV channels. We note  $(e_{i-1})_{jk} = 1$  if the TV channel  $k$  is to be served and zero otherwise
- $P_c(R_D, (\mathbf{e}_{i-1})_{j*})$  and  $C_L(R_D, (\mathbf{e}_{i-1})_{j*})$  are the power consumption (Eqn. (4.3)) and the additional cost of LTE infrastructure sites (Eqn. 4.6)) when the DVB coverage radius is  $R_D$  and the set of TV channels to be served is  $(\mathbf{e}_{i-1})_{j*}$ .

iii. The operator share in the broadcast equipments and infrastructure rent costs is:

$$\phi_o^{rent}(R_D, P_o, V_c^{rent}) = \frac{N-1}{N} \cdot C_D^{rent} \quad (4.19)$$

iv. The operator share of the content costs (Eqn. (4.20)) is calculated by the same way as Eqn. (4.14)) given the worth function  $V_c^{content}(R_D, S) = (\sum_{i=1/|i \in (S)}^{|\mathbf{K}_{\mathbf{TV}}|} c_i) I_{\{operator \in (S)\}}$ :

$$\phi_o^{content}(R_D, P_o, V_c^{content}) = \sum_{i=1}^{|\mathbf{K}_{\mathbf{TV}}|} \frac{c_i}{2} \quad (4.20)$$

The overall cost share of the operator  $\phi_o^c(R_D, P_o, V_c)$  is the sum of these four components.

By the balance property defined in Eqn. (4.9), we obtain the cost share of channel

provider  $i$  as a function of the cost share of the operator:

$$\phi_i^c(R_D, P_o, V_c) = \phi_o^c(R_D, P_o, V_c) - \phi_o^c(R_D, P_o \setminus \{i\}, V_c) \quad (4.21)$$

#### 4.3.3.3 Illustration of profit sharing

The profit distribution of each player is simply the difference between its revenue share and cost share derived above.

To illustrate profit sharing between players in the system, we consider the input parameters shown in Table 4.1:

Number of subscribers	200000
Monthly LTE infrastructure costs $\alpha_L$ [euros/month]	833*
Total Content Costs [euros]	2000
Number of TV channels	5 channels
TV channels requirements [Kbps]	512 each **
Total subscriber fees [euros/month]	7
ISD in the existent DVB system [Km]	43.31

\* Price of an e-Node=30000 euros , Life time is 3 Years, so the cost is in average 833 [euros/month]

\*\* The MODCOD 16-QAM 3/5 is satisfactory

Table 4.1: Profit sharing: Input Parameters

We implement on MATLAB the closed-form expressions we derived above. We plot in Figure 4-3 the single operator profit for a set of 5 TV channels with a required capacity of 512 Kbps each (as indicated in Table 4.1), as a function of increasing DVB radius  $R_D$  (equivalently, increasing transmission power  $P_D$ ) until we reach the service area radius  $R_S = \frac{ISD}{2 \cdot \cos(30)} = 25$  Km (eq. (2.1)). As the electricity price is a parameter that depends on the country (e.g., its energy policy and the availability of a reliable electricity grid), we plot the profit for different values of electricity prices.

As we can see from Figure 4-3, the profit of the operator always increases when DVB coverage increases for a low electricity price. This is however not true when the electricity price is high, in which case profit reaches a maximum for a certain DVB radius  $R_D$  and decreases when this radius exceeds a certain limit. This  $R_D$  limit decreases with the increase of the electricity costs. So, for electricity cost remarkably lower than the LTE infrastructure, the operator has an incentive to choose to offer mobile TV by DVB bearer alone. It would however use both LTE and DVB infrastructures in an optimal network configuration ( $R_D$  maximizing the profit) when the

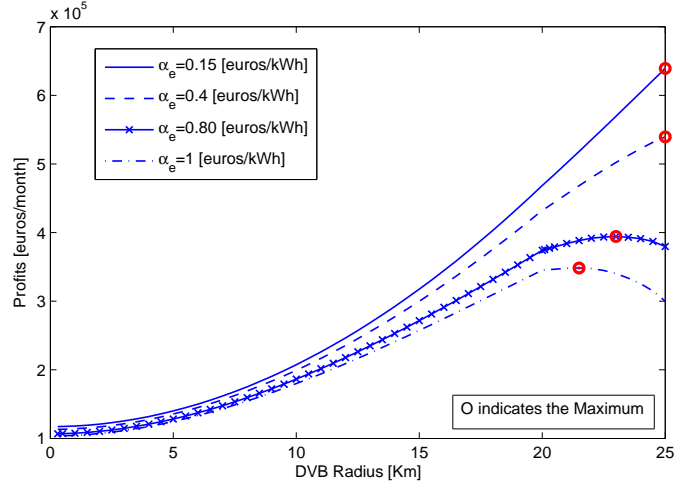


Figure 4-3: Profits of the operator for different DVB radius  $R_D$  and different values of electricity costs

electricity and cellular costs are comparable.

The profit earned by a channel provider depends on its contribution to the revenues. For a set of 5 TV channels  $\mathbf{K}_{\mathbf{TV}} = [TV_1 \ TV_2 \ TV_3 \ TV_4 \ TV_5]$  with total subscription fees 7 (euros/month), as indicated in Table 4.1, and considering that TV channel popularities are given by Zipf distribution with parameter  $\alpha_{Zipf} = 1.1$ , the individual subscription fees of each TV channel is thus estimated as [3.25 1.51 0.97 0.71 0.55] (euros) (Sec. 4.3.3.1); the profit of each channel provider is illustrated in Figure 4-4.

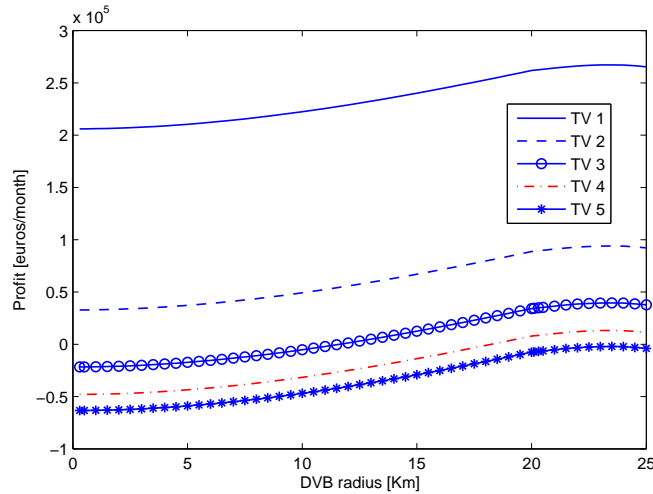


Figure 4-4: Profit share of the TV channels when  $\alpha_e = 0.4$  and  $\alpha_L = 833$

At this point, we can prove by counterexample that the Shapley Value is not always stable (Sec. 4.3.2). In fact, we can see that the lower revenue channels (which

can represent niche channels) might experience, for certain network configurations (in our case for  $R_D = 25$  Km), a negative profit and decide to leave this coalition (the negative value of profit is not the only case for leaving the coalition, a channel may leave if its profit does not reach a certain target). And so, for solid dimensioning, the operator has to find a stable set of TV channels, where none of them has the incentive to leave the coalition. This is discussed in the next section.

#### 4.3.3.4 Evolution of the coalition and Nash equilibrium

When a player finds itself unsatisfied by its profits, it will act to increase its gains or leave the game. The operator set of actions  $A_o$  is the set of possible transmission powers ( $A_o = \{P_D\}$ ). A channel has two actions: either decide to enter the game and be broadcast, or leave the system following its profit target (recall Figure 4-4). The game evolves until reaching a network configuration and a set of TV channels where all the players are satisfied and do not have incentive to leave, defining the Nash Equilibrium (NE)[13].

Formally, the Nash equilibrium is defined in [75] as the set  $A^* = (a_1^*, \dots, a_N^*)$ , defining the action  $a_i^*$  of each player  $i$ . It has the property that no player  $i$  can do better by choosing an action different from  $a_i^*$ , given that every other player  $j$  adheres to  $a_j^*$ . Based on this definition, we implement on MATLAB the Best Response method [75] to compute the Nash Equilibrium of the system.

For the numerical setting of Table 4.1 and for an electricity costs  $\alpha_e = 0.4$  (euros/month), we find that the equilibrium corresponds to the combination of the 4 most popular TV channels with a network completely covered by DVB ( $R_D = 25$  Km), assuming that the TV channel providers will accept any positive profit. This means that it is more profitable for the operator, in this case, to use a DVB infrastructure for delivering the mobile TV service, and to reserve LTE system to unicast services. Even though channel TV<sub>5</sub> is not to be served, the operator will gain more profit than if it was delivered, since it entails high costs while having very low revenues.

#### 4.3.4 Profit sharing strategy: Case of separate LTE and DVB operators

We now consider the case where the LTE and DVB operators are separate. The set of players becomes  $P_1$ , and includes the LTE operator with  $X_L$  subscribers offering a TV bouquet  $\mathbf{K}_{TV}^L$  with subscription fees of  $\delta_L$  per user, the DVB operator with a subscribers database  $X_D$  and offering a TV bouquet  $\mathbf{K}_{TV}^D$  with subscription fees of  $\delta_D$  per user and finally the  $K = |\mathbf{K}_{TV}^L| + |\mathbf{K}_{TV}^D| - |\mathbf{K}_{TV}^{com}|$  TV channel owners ( $|\mathbf{K}_{TV}^{com}|$  is

the set of TV channels that are offered by both LTE and DVB standalone networks). We now proceed with the profit distribution and coalition evolution analysis, as we did for the single operator case in the previous section.

#### 4.3.4.1 Revenue Sharing

As stated previously (Section 4.3.3.1), each channel  $i$  has an amount of subscription fees proportional to its popularity. The revenues generated by a TV channel  $i$  are given by  $\delta_i^L = p(i)\delta_L X'_L$  on standalone LTE bearer ( $L$ ) and  $\delta_i^D = p(i)\delta_D X'_D$  on standalone DVB bearer ( $D$ ) ( $X'_L$  and  $X'_D$  are given in eq. (4.1)). We recall that in the cooperative scenario these revenue are not a simple summation of the previously introduced ones (section 4.3.1) but are given as being  $\delta_i^{coop} = p(i)\delta_{coop}(X_L + X_D - \frac{X_{com}}{2})$ , with  $X_{com}$  is the common portion in LTE and DVB subscriber base and  $\delta_{coop}$  is the subscription fee per user in this network.

On the other side, for the hybrid network configuration shown in Figure 2-5, we consider that each channel  $i$  is broadcast by DVB in DVB coverage region and by LTE in regions where this channel cannot be served by DVB, so as to ensure continuity of mobile TV service delivery. So, the revenue worth function of a certain subset of players defined by coalition  $S$  could be seen as the addition of the elementary revenue worth functions  $V_r^n(S)$  defined by:

$$V_r^n(S) = \delta_i^L \cdot I_{\{\{L,i\} \in (S), \{D\} \notin (S)\}} + \delta_i^D \cdot I_{\{\{D,i\} \in (S), \{L\} \notin (S)\}} + \delta_i^{coop} \cdot I_{\{\{L,D,i\} \in (S)\}} \quad (4.22)$$

where  $I_C = 1$  if condition  $C$  is true and 0 otherwise.

Given  $(S, V_r^n)$ , we begin by the LTE share and reason as in Section 4.3.3.1: We eliminate the dummy players (which are any channel  $j \neq i$ ) and apply Shapley distribution (Eq. (4.7)) to the rest ( $L$ ,  $D$  and  $i$ ). We aggregate then the elementary shares to obtain:

$$\begin{aligned} \phi_L^r(R_D, P_1, V_r') &= \sum_{i=1}^K \frac{2 \cdot \delta_i^{coop} + \delta_i^L}{6} \cdot I_{(i \in \mathbf{K}_{TV}^L \text{ and } i \notin \mathbf{K}_{TV}^D)} \\ &\quad + 2 \cdot \frac{\delta_i^{coop} - \delta_i^D}{6} \cdot I_{(i \in \mathbf{K}_{TV}^D \text{ and } i \notin \mathbf{K}_{TV}^L)} \\ &\quad + \frac{2 \cdot \delta_i^{coop} + \delta_i^L - 2 \cdot \delta_i^D}{6} \cdot I_{(i \in \mathbf{K}_{TV}^L \text{ and } \mathbf{K}_{TV}^D)} \end{aligned} \quad (4.23)$$

We do the same to obtain the DVB profit share:

$$\begin{aligned}\phi_D^r(R_D, P_1, V_r') &= \sum_{i=1}^K 2 \cdot \frac{\delta_i^{coop} - \delta_i^L}{6} \cdot I_{(i \in \mathbf{K}_{TV}^L \text{ and } i \notin \mathbf{K}_{TV}^D)} \\ &\quad + \frac{2 \cdot \delta_i^{coop} + \delta_i^D}{6} \cdot I_{(i \in \mathbf{K}_{TV}^D \text{ and } i \notin \mathbf{K}_{TV}^L)} \\ &\quad + \frac{2 \cdot \delta_i^{coop} + \delta_i^D - 2 \cdot \delta_i^L}{6} \cdot I_{(i \in \mathbf{K}_{TV}^L \text{ and } \mathbf{K}_{TV}^D)}\end{aligned}\quad (4.24)$$

Finally the share of elementary channel  $i$  is given by:

$$\begin{aligned}\phi_i^r(R_D, P_1, V_r') &= \frac{2 \cdot \delta_i^{coop} + \delta_i^L}{6} \cdot I_{(i \in \mathbf{K}_{TV}^L \text{ and } i \notin \mathbf{K}_{TV}^D)} + \frac{2 \cdot \delta_i^{coop} + \delta_i^D}{6} \cdot I_{(i \in \mathbf{K}_{TV}^D \text{ and } i \notin \mathbf{K}_{TV}^L)} \\ &\quad + \frac{2 \cdot \delta_i^{coop} + \delta_i^D + \delta_i^L}{6} \cdot I_{(i \in \mathbf{K}_{TV}^L \text{ and } \mathbf{K}_{TV}^D)}\end{aligned}\quad (4.25)$$

We can verify that the efficiency property (eq. (4.8)) holds:

$$\begin{aligned}\phi_L^r(R_D, P_1, V_r') + \phi_D^r(R_D, P_1, V_r') + \sum_i^K \phi_i^r(R_D, P_1, V_r') \\ = \sum_{i=1}^K \delta_i^{coop} \cdot I_{(i \in \mathbf{K}_{TV}^L \text{ and } i \notin \mathbf{K}_{TV}^D)} + \delta_i^{coop} \cdot I_{(i \in \mathbf{K}_{TV}^D \text{ and } i \notin \mathbf{K}_{TV}^L)} + \delta_i^{coop} \cdot I_{(i \in \mathbf{K}_{TV}^L \text{ and } \mathbf{K}_{TV}^D)} \\ = \sum_{i=1}^K \delta_i^{coop}\end{aligned}\quad (4.26)$$

#### 4.3.4.2 Cost Sharing

The system total costs will be shared by all players (i.e., LTE will pay a share in the DVB cost and vice versa). In this case also, we divide the costs worth function using the additivity property into four elementary worth functions:

i- Power consumption worth function:

$$V_c'^P(R_D, S) = P_c(R_D, S \setminus \{D, L\})I_{\{D, L \in (S)\}} + P_c(R_s, S \setminus \{D\})I_{\{D \in (S), L \notin (S)\}} \quad (4.27)$$

where  $R_S$  is the radius of the target service area,  $R_D$  is the radius of the area covered by DVB (see Figure 2-5),  $L$  and  $D$  represent the LTE and DVB operators respectively,  $P_c(R_D, S \setminus \{D, L\})$  is the DVB power consumption when the latter covers only a region of radius  $R_D$  (Eqn. (4.3)) and cooperate with LTE to serve the set of TV



channels existing in coalition ( $S$ ) (all players other than the operator and represented by  $S \setminus \{D, L\}$ ) and finally  $P_c(R_S, S \setminus \{D\})$  is the maximal power consumption costs when DVB covers the total service area of radius  $R = R_S$  and serves alone the Mobile TV service defined by the set of TV channels in coalition ( $S$ ) (i.e.,  $S \setminus \{D\}$  since  $D$  is the only operator in this case).

Using Eqn. (4.7), we obtain the share of DVB in power consumption  $\phi_D^P(R_D, P_1, V_c'^P)$  (see Appendix E for derivation details):

$$\begin{aligned} \phi_D^P(R_D, P_1, V_c^P) = & \alpha_e \cdot H \frac{\sum_{i=2}^{N_1-1} i(i-1)! \left( \sum_{j=1}^{m_{i-1}} P_c(R_D, (\mathbf{e}_{i-1})_{j*}) \right) (N_1 - i - 1)!}{N_1!} \\ & + \alpha_e \cdot H \frac{\sum_{i=2}^{N_1-1} (i-1)! \left( \sum_{j=1}^{m_{i-1}^D} P_c(R_S, (\mathbf{e}_{i-1}^D)_{j*}) \right) (N_1 - i)!}{N_1!} \end{aligned} \quad (4.28)$$

By the balance property (Eqn. (4.9)), we obtain the broadcast power transmission share due to LTE operator (Eqns. (4.29)):

$$\begin{aligned} \phi_L^P(R_D, P_1, V_c^P) = & \alpha_e \cdot H \frac{\sum_{i=2}^{N_1-1} i(i-1)! \left( \sum_{j=1}^{m_{i-1}} P_c(R_D, (\mathbf{e}_{i-1})_{j*}) \right) (N_1 - i - 1)!}{N_1!} \\ & - \alpha_e \cdot H \frac{\sum_{i=2}^{N_1-1} i(i-1)! \left( \sum_{j=1}^{m_{i-1}^D} P_c(R_S, (\mathbf{e}_{i-1}^D)_{j*}) \right) (N_1 - i - 1)!}{N_1!} \end{aligned} \quad (4.29)$$

where, again,  $N_1$  is the total number of players ( $N_1 = K + 2$ ),  $\mathbf{e}_{i-1}$  is the same ( $m_{i-1} \times |\mathbf{K}_{\mathbf{TV}}|$ ) matrix defined in Section 4.3.3.2, the set of TV channels to be served is given by its  $j^{th}$  line  $(\mathbf{e}_{i-1})_{j*}$  and  $P_c(R_D, (\mathbf{e}_{i-1})_{j*})$  is the power consumption (Eqn. (4.3)) needed when the DVB coverage radius is  $R_D$ . A new matrix,  $\mathbf{e}_{i-1}^D$  appears in this case, its structure is similar to  $\mathbf{e}_{i-1}$  except that it represents the combinations of  $i - 1$  TV channels served only by DVB if we consider the standalone scenario ( $i \in \mathbf{K}_{\mathbf{TV}}^D, i \notin \mathbf{K}_{\mathbf{TV}}^L$ ).

ii- DVB transmitter and equipments rent costs worth function:

The term  $C_D^{rent}$  in Eqn. (4.4) is due to the rent of the DVB transmitter and equipment from fixed TV operator or their updates to deliver mobile TV by DVB operator. The rent worth function is:

$$V_c'^{rent}(R_D, S) = C_D^{rent} I_{\{D \in (S)\}} \quad (4.30)$$

The broadcast transmitter and LTE rent costs,  $\phi_D^{rent}(P_1, V_c^{rent})$  and  $\phi_L^{rent}(P_1, V_c^{rent})$  respectively, are obtained by replacing both  $P_c(R_S, (\mathbf{e}_{i-1})_{j*})$  and  $P_c(R_S, (\mathbf{e}_{i-1}^D)_{j*})$  in the previous equations (eqs. (4.28) and (4.29)) by the constant cost  $C_D^{rent}$ .

Finally, we obtain each TV channel  $i$  broadcast costs (power consumption and equipment rent costs) share (also by applying the balance property):

$$\begin{aligned} \phi_i^{P'}(R_D, P_1, V_c^{D'}) &= \phi_D^{P'}(R_D, P_1, V_c^{D'}) + \phi_D^{rent}(R_D, P_1, V_c^{rent}) \\ &\quad - (\phi_D^{P'}(R_D, P_1 \setminus \{i\}, V_c^{D'}) + \phi_L^{rent}(R_D, P_1 \setminus \{i\}, V_c^{rent})) \end{aligned} \quad (4.31)$$

iii- LTE infrastructure worth function:

$$V_c^{bs}(S) = C_L(R_D, S \setminus \{L, D\})I_{\{L, D \in (S)\}} + C_L(R_S, S \setminus \{L\})I_{\{L \in (S), D \notin (S)\}} \quad (4.32)$$

where  $C_L(R_D, S \setminus \{L, D\})$  is the additional infrastructure costs induced when we serve the set  $S \setminus \{L, D\}$  of TV channels without any compromise on unicast services quality, in a cooperative LTE and DVB system (Eqn. 4.6), and  $C_L(R_S, S \setminus \{L, D\})$  is the maximal additional infrastructure costs in a standalone system where LTE covers the whole service area of radius  $R_S$ .

Using Eqn. (4.7) and the other Shapley value properties, we obtain the infrastructure distribution (i.e., the share each player has to pay for the total cellular infrastructure costs). The infrastructure costs share of LTE and DVB are given respectively in Eqns. (4.33) and (4.34) (see Appendix E for derivation details).

$$\begin{aligned} \phi_L^{bs}(R_D, P_1, V_c^{bs}) &= \frac{\sum_{i=2}^{N_1-1} i(i-1)! \left( \sum_{j=1}^{m_{i-1}} C_L(R_D, (\mathbf{e}_{i-1})_{j*}) \right) (N_1 - i - 1)!}{N_1!} \\ &\quad + \frac{\sum_{i=2}^{N_1-1} (i-1)! \left( \sum_{j=1}^{m_{i-1}^L} C_L(R_S, (\mathbf{e}_{i-1}^L)_{j*}) \right) (N_1 - i)!}{N_1!} \end{aligned} \quad (4.33)$$

and

$$\begin{aligned} \phi_D^{bs}(R_D, P_1, V_c^{bs}) &= \frac{\sum_{i=2}^{N_1-1} i(i-1)! \left( \sum_{j=1}^{m_{i-1}} C_L(R_D, (\mathbf{e}_{i-1})_{j*}) \right) (N_1 - i - 1)!}{N_1!} \\ &\quad - \frac{\sum_{i=2}^{N_1-1} i(i-1)! \left( \sum_{j=1}^{m_{i-1}^L} C_L(R_S, (\mathbf{e}_{i-1}^L)_{j*}) \right) (N_1 - i - 1)!}{N_1!} \end{aligned} \quad (4.34)$$

where again,  $\mathbf{e}_{i-1}$  is a  $(m_{i-1} \times |\mathbf{K}_{\mathbf{TV}}|)$  matrix representing the possible combination of served channels by LTE and DVB. The set of TV channels to be served is given by its  $j^{th}$  line  $(\mathbf{e}_{i-1})_{j*}$ .  $\mathbf{e}_{i-1}^L$  is similar to  $\mathbf{e}_{i-1}$  except that it represents the combinations of  $i-1$  TV channels served only by LTE if we consider the standalone scenario ( $i \in \mathbf{K}_{\mathbf{TV}}^L, i \notin \mathbf{K}_{\mathbf{TV}}^D$ )

Again, by applying the balance property (Eqn. (4.9)), we obtain the infrastructure cost share of each TV channel  $i$ :

$$\phi_i^{bs'}(R_D, P_1, V_c^{bs}) = \phi_L^{bs}(R_D, P_1, V_c^{bs}) - \phi_L^{bs'}(R_D, P_1 \setminus \{i\}, V_c^{bs}) \quad (4.35)$$

iv- Content costs worth function:

$$V_c'^C(S) = \left[ \sum_{i=1}^K c_i \right] I_{\{D \text{ and/or } L \text{ and } i \in (S)\}} \quad (4.36)$$

Calculations lead to the following distribution:

$$\phi_D'^{content}(P_1, V_c'^{content}) = \sum_{i=1}^K \frac{3 \cdot c_i}{6} \cdot I_{(i \in \mathbf{K}_{\mathbf{TV}}^D \text{ and } i \notin \mathbf{K}_{\mathbf{TV}}^L)} + \frac{c_i}{6} \cdot I_{(i \in \mathbf{K}_{\mathbf{TV}}^L \text{ and } \mathbf{K}_{\mathbf{TV}}^D)} \quad (4.37)$$

$$\phi_L'^{content}(P_1, V_c'^{content}) = \sum_{i=1}^K \frac{3 \cdot c_i}{6} \cdot I_{(i \in \mathbf{K}_{\mathbf{TV}}^L \text{ and } i \notin \mathbf{K}_{\mathbf{TV}}^D)} + \frac{c_i}{6} \cdot I_{(i \in \mathbf{K}_{\mathbf{TV}}^L \text{ and } \mathbf{K}_{\mathbf{TV}}^D)} \quad (4.38)$$

$$\begin{aligned} \phi_i'^{content}(P_1, V_c'^{content}) &= \sum_{i=1}^K \frac{3 \cdot c_i}{6} \cdot I_{(i \in \mathbf{K}_{\mathbf{TV}}^L \text{ and } i \notin \mathbf{K}_{\mathbf{TV}}^D)} + \frac{3 \cdot c_i}{6} \cdot I_{(i \in \mathbf{K}_{\mathbf{TV}}^D \text{ and } i \notin \mathbf{K}_{\mathbf{TV}}^L)} \\ &\quad + \frac{4 \cdot c_i}{6} \cdot I_{(i \in \mathbf{K}_{\mathbf{TV}}^L \text{ and } \mathbf{K}_{\mathbf{TV}}^D)} \end{aligned} \quad (4.39)$$

where, again,  $L$  refers to the LTE operator,  $D$  to DVB and  $c_i$  is the content cost of TV channel  $i$ .

#### 4.3.4.3 Incentives for cooperation to minimize the operators costs

Thanks to its “fairness”, the profit distribution under Shapley value is appealing in cooperative games. Each player is rewarded a profit proportional to its contribution in the overall profit.

**Proposition 5** *Under the Shapley profit distribution, LTE and DVB operators targeting the same set of TV channels ( $\mathbf{K}_{\mathbf{TV}}^L = \mathbf{K}_{\mathbf{TV}}^D$ ) always have the incentive to*

cooperate to reduce their costs when offering mobile TV service.

**Proof:** We have to prove that the cost share of DVB and LTE operators in the cooperative network is lower than the standalone network cost share by proving Eqns. (4.40) and (4.41) respectively:

$$\phi_D^c(R_D, P_1, V'_c) \leq \phi_D^c(R_S, P_1 \setminus \{L\}, V'_c) \quad (4.40)$$

and

$$\phi_L^c(R_D, P_1, V'_c) \leq \phi_L^c(R_S, P_1 \setminus \{D\}, V'_c) \quad (4.41)$$

We begin by the DVB cost; it is given by the sum of equations (4.28), (4.34) and (4.37) in a cooperative LTE/DVB network and can be written as:

$$\begin{aligned} \phi_D^c(R_D, P_1, V'_c) = & \phi_D^P(R_D, P_1, V_c'^P) \\ & + \phi_L^{bs}(R_D, P_1, V_c'^{bs}) - \phi_L^{bs}(R_S, P_1 \setminus \{D\}, V'_c) \\ & + \sum_{i=1}^K \frac{c_i}{6} \end{aligned} \quad (4.42)$$

and in a standalone DVB network it is given by:

$$\begin{aligned} \phi_D^c(R_S, P_1 \setminus \{L\}, V'_c) = & \phi_D^P(R_S, P_1 \setminus \{L\}, V'_c) \\ & + \sum_{i=1}^K \frac{c_i}{2} \end{aligned} \quad (4.43)$$

DVB has the incentive to cooperate with LTE if we can prove that:

$$\begin{aligned} & \phi_D^P(R_D, P_1, V_c'^P) + \phi_L^{bs}(R_D, P_1, V_c'^{Lbs}) \\ & + \sum_{i=1}^K \frac{c_i}{6} \\ & \leq \phi_D^P(R_S, P_1 \setminus \{L\}, V'_c) + \phi_L^{bs}(R_S, P_1 \setminus \{D\}, V'_c) \\ & + \sum_{i=1}^K \frac{c_i}{2} \end{aligned} \quad (4.44)$$

This is true as:

$$\begin{aligned} & \phi_D^P(R_D, P_1, V_c'^P) - \phi_D^P(R_S, P_1 \setminus \{L\}, V'_c) = \\ & \phi_L^P(R_D, P_1, V_c'^P) \end{aligned} \quad (4.45)$$

where  $\phi_L^P(R_D, P_1, V_c'^P)$  is the LTE power costs share given by eq. (4.29). This later can easily be proved to be negative when the LTE and DVB target the same set of

TV channels ( $\mathbf{K}_{\mathbf{TV}}^L = \mathbf{K}_{\mathbf{TV}}^D$  and thus  $\mathbf{e}_{i-1} = \mathbf{e}_{i-1}^D$ ). In fact, the transmitted power and hence the consumed one for a given set of served TV channels  $(\mathbf{e}_{i-1})_{j^*}$  and covering the whole service area ( $R_D = R_S$ ) is higher than the power needed to cover only a portion of the area ( $R_D < R_S$ ):  $P_c(R_S, (\mathbf{e}_{i-1})_{j^*}) \geq P_c(R_D, (\mathbf{e}_{i-1})_{j^*})$ . Let's note that  $\phi_L^P(R_D, P_1, V_c'^P)$  is seen in this case as the gain paid by the DVB operator to LTE for using LTE's infrastructure to offer mobile TV in the outer region (Fig. 2-5) and thus reducing its (DVB's) transmission power.

so:

$$\phi_D^P(R_D, P_1, V_c'^P) \leq \phi_D^P(R_S, P_1 \setminus \{L\}, V_c') \quad (4.46)$$

In the same way we prove:

$$\phi_L^{bs}(R_D, P_1, V_c'^{bs}) \leq \phi_L^{bs}(R_S, P_1 \setminus \{D\}, V_c') \quad (4.47)$$

Finally:  $\sum_{i=1}^K \frac{c_i}{6} < \sum_{i=1}^K \frac{c_i}{2}$ . By adding those inequalities we obtain our goal equation (4.44).

In the same way we prove eq. (4.41).

Finally we conclude that under the shapley distribution both LTE and DVB operators always have the incentive for cooperation to reduce their networks costs when they target the same TV channel set.  $\square$

The incentive of cooperation and the fairness of the profit distribution under Shapley value mechanism do not mean the absence of disputes and competition between players. In fact, each player in this game will seek the network configuration that maximizes its individual profit (in our case, the network configuration corresponds to radius  $R_D$ , i.e., area covered by DVB in Fig. 2-5).

We also prove the following proposition:

**Proposition 6** *Under the Shapley profit distribution, both LTE and DVB operators have the same optimal configuration ( $R_D$ ) that minimizes their cost share.*

**Proof:** If we consider  $R_D^*$  the optimal radius of DVB area that maximizes the profit of LTE:

$$\phi_L^c(R_D^*, P_1, V_c') \leq \phi_L^c(R_D, P_1, V_c') \quad (4.48)$$

By detailing the cost share  $\phi_L^c$ , into power, infrastructure and content costs we obtain:

$$\begin{aligned}
& \phi_L^{bs}(R_D^*, P_1, V_c'^{bs}) + \phi_D^P(R_D^*, P_1, V_c'^P) \\
& - \phi_D^P(R_S, P_1 \setminus \{L\}, V_c') \\
& \leq \phi_L^{bs}(R_D, P_1, V_c'^{bs}) + \phi_D^P(R_D, P_1, V_c'^P) \\
& - \phi_{DVB}^P(R_S, P_1 \setminus \{L\}, V_{c'})
\end{aligned} \tag{4.49}$$

We can easily omit the standalone DVB constant costs  $\phi_D^P(R_S, P_1 \setminus \{L\}, V_c'^P)$  and introduce the standalone LTE constant costs  $\phi_L^{bs}(R_S, P_1 \setminus \{D\}, V_c')$

$$\begin{aligned}
& \phi_L^{bs}(R_D^*, P_1, V_c'^{bs}) + \phi_D^{bs}(R_D^*, P_1, V_c'^P) \\
& - \phi_L^{bs}(R_S, P_1 \setminus \{D\}, V_c'^{bs}) \\
& \leq \phi_L^{bs}(R_D, P_1, V_c'^{bs}) + \phi_D^P(R_D, P_1, V_c'^P) \\
& - \phi_L^{bs}(R_S, P_1 \setminus \{D\}, V_c'^{bs})
\end{aligned} \tag{4.50}$$

by reorganizing the terms we obtain:

$$\begin{aligned}
& \phi_D^P(R_D^*, P_1, V_c'^P) + \phi_L^{bs}(R_D^*, P', V_c'^{bs}) \\
& - \phi_L^{bs}(P' \setminus \{D\}, V_c'^{bs}) \\
& \leq \phi_D^P(R_D, P', V_c'^P) + \phi_L^{bs}(R_D, P_1, V_c'^{bs}) \\
& - \phi_L^{bs}(R_S, P_1 \setminus \{D\}, V_c'^{bs})
\end{aligned} \tag{4.51}$$

and finally:

$$\phi_D^c(R_D^*, P_1, V_c') \leq \phi_D^c(R_D, P_1, V_c') \tag{4.52}$$

□

We note that this proposition is always true, whatever is the set of TV channels  $\mathbf{K}_{TV}^L$  and  $\mathbf{K}_{TV}^D$ .

#### 4.3.4.4 Illustrations of the profits

We consider the inputs given in Table 4.1 in Section 4.3.3.3.

We plot in Figures 4-5 and 4-6 the costs paid by both LTE and DVB operators for moderate ( $\alpha_e = 0.18$ ) and high ( $\alpha_e = 0.8$ ) electricity price, respectively. We observe that under the Shapley distribution, both LTE and DVB operators will agree on the same network configuration choice ( $R_D$ ) as proved in Section 4.3.4.3. Indeed, both operators have the lowest induced costs for  $R_D = 25Km$  for moderate electricity price level and  $R_D = 23Km$  for higher electricity price. This means that the best config-

uration is to use the infrastructure of the network with the lowest cost as compared to the other network.

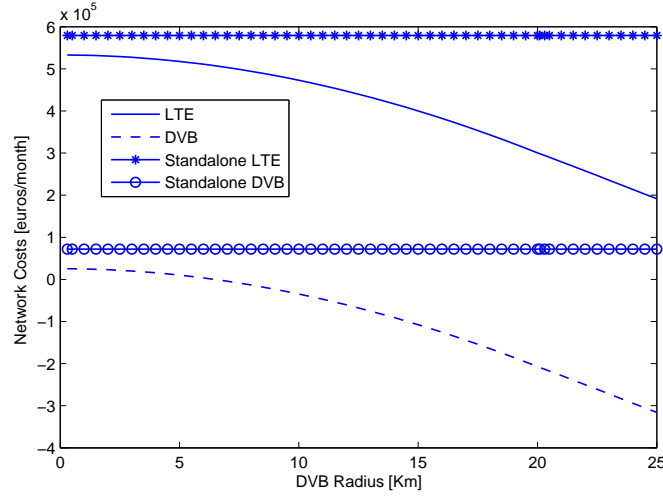


Figure 4-5: Operators Cost Share (Power and Infrastructure) for  $\alpha_e = 0.18$  euros/kWh

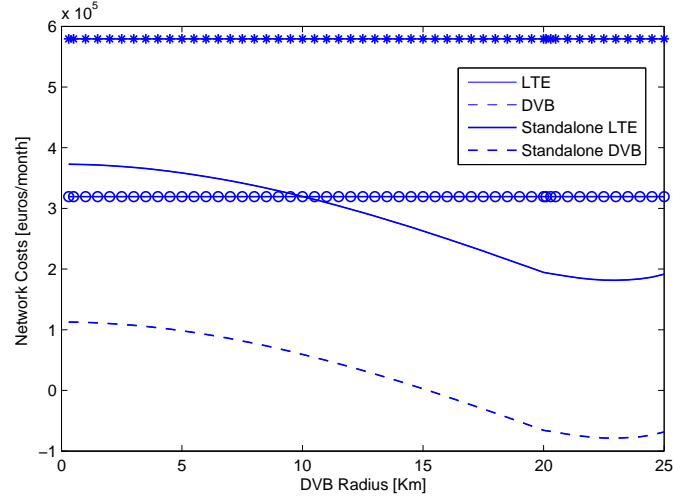


Figure 4-6: Operators Cost Share (Power and Infrastructure) for  $\alpha_e = 0.8$  euros/month

It is also clear that for both electricity price levels, the mobile TV network costs paid by the operators in a hybrid network are lower than those paid in a standalone network, even when the optimal network configuration is to use only one operator (as for  $\alpha_e = 0.18$  and the optimal network configuration is to cover the whole area with DVB signal  $R_D = 25Km$ ). This is due to the fact that under Shapley profit distribution, not only the revenue but also the network costs are shared fairly among the

players. As a result, the LTE operator will pay DVB an amount of  $\phi_D^{bs}(R_D, P_1, V_c'^{bs})$  euros/month (Eqn. (4.34)), for offloading a part of its traffic on DVB infrastructure at lower costs. These new DVB revenues are shown in Figure 4-7 as being a negative cost share.

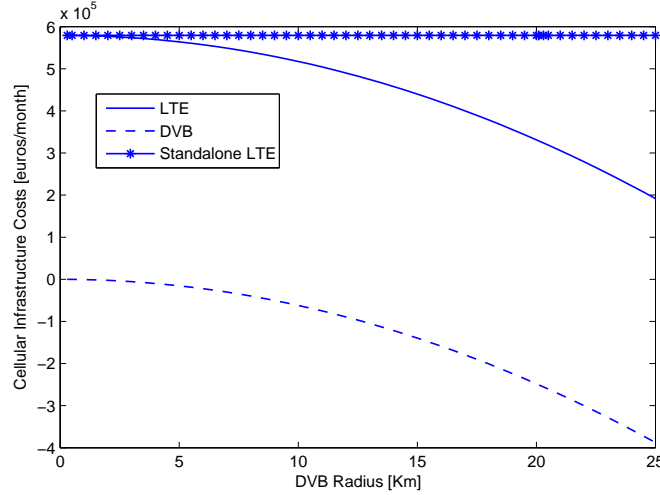


Figure 4-7: Operators' Cellular Infrastructure Costs Share for  $\alpha_e = 0.18$  euros/kWh

The DVB operator will also pay LTE an amount of  $\phi_L^P(R_D, P_1, V_c'^P)$  euros/month (Eqn. (4.29)), represented by the negative power cost share of LTE in Figure 4-8.

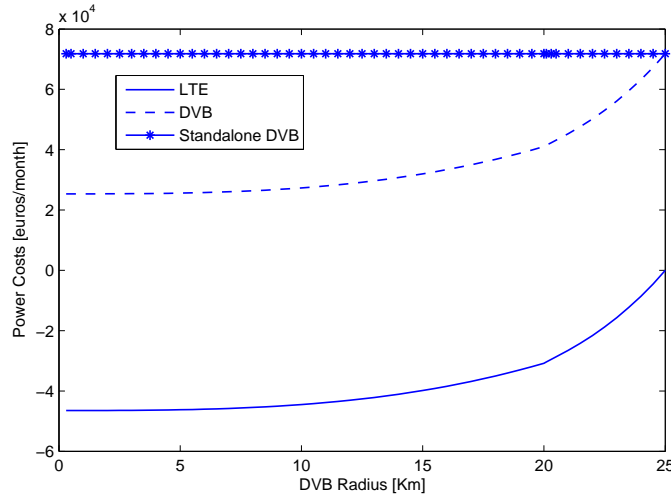


Figure 4-8: Operators' Power Costs Share for  $\alpha_e = 0.18$  euros/kWh

We next plot, in Figure 4-9, the profit for each operator for two penetration percentages: one with 80% subscribers for LTE and 20% subscribers for DVB, and one with 50% each. For a moderate electricity price of 0.18 euros/month.



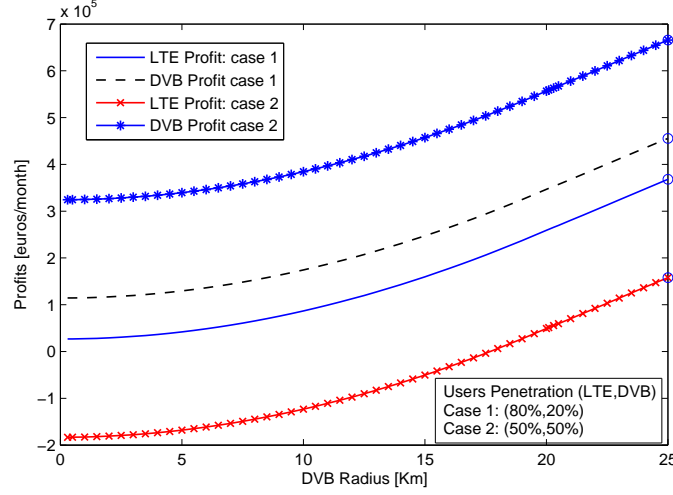


Figure 4-9: Profits of the operator for different DVB subscription penetration with  $\alpha_e = 0.18$  euros/kWh

We observe that for the low LTE user penetration rate (50 %), LTE will not be able to serve the mobile TV users alone; if LTE does not increase its subscription fees, its profits will be negative in a standalone network. If it however cooperates with DVB, it will be able to serve mobile TV without increasing its subscription fees and its profit will be positive starting from  $R_D \geq 18$  Km.

In Figure 4-10 we plot the profit shares of the TV channels, LTE and DVB operators for an equal users penetration rate (50 %) and for an electricity price  $\alpha_e = 0.4$  euros/kWh.

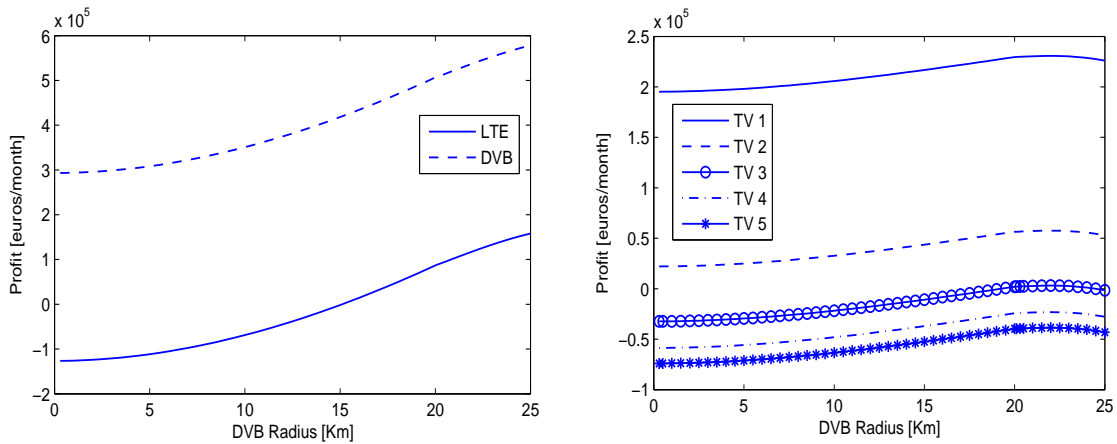


Figure 4-10: Operators and Channel providers profits for equal user penetration and  $\alpha_e = 0.4$  euros/kWh

We see that TV channels 5, 4 and 3 have negative profit under the optimal LTE and

DVB network configuration setting ( $R_D = 25 \text{ km}$ ), and they will not have incentive to take part in this offer.

This implies that, once again, this model have to be coupled with a Nash Equilibrium study to define the stable coalition. In this case, we have  $(|\mathbf{K}_{\text{TV}} + \mathbf{K}_{\text{DVB}} - \mathbf{K}_{\text{com}}| + 2)$  players:  $K = |\mathbf{K}_{\text{TV}} + \mathbf{K}_{\text{DVB}} - \mathbf{K}_{\text{com}}|$  channel providers, each offering one TV channel, LTE and DVB operators. The players action profiles are defined as follows:

- LTE operator can choose whether to cooperate with DVB to deliver the mobile TV service alone (using only its own infrastructure). If LTE cooperates, it dimensions its system so as to cover all the area not covered by DVB. The corresponding set of actions is  $A_L = \{\text{cooperation}, \text{no cooperation}\}$ .
- DVB operator enters the game by adjusting its transmission power either cooperatively with LTE or by setting it to some maximal value on its own in case it decides or LTE decides not to cooperate. The corresponding action is  $A_D = \{\text{cooperation}(P_D), \text{no cooperation}\}$ .
- The channel providers decide whether they wish to be broadcast or not (with respect to their target profits) when the operators decide to cooperate, or which operator to join (or both or none) when the latter decide not to cooperate. The actions for the cooperative case are  $A_i^{\text{coop}} = \{\text{broadcast}, \text{not broadcast}\}$ , and for the non-cooperative case are  $A_i^{\text{no-coop}} = \{\text{not broadcast}, \text{LTE}, \text{DVB}, \text{LTE and DVB}\}$ .

For the particular case of figure 4-10, LTE and DVB operators will have four Nash equilibria (stable dimensioning strategies):

1. LTE/DVB cooperation; set of TV channels:  $\text{TV}_1, \text{TV}_2, \text{TV}_4, \text{TV}_5$ ;  $R_D = 25 \text{ Km}$
2. LTE/DVB cooperation; set of TV channels:  $\text{TV}_1, \text{TV}_2, \text{TV}_3, \text{TV}_5$ ;  $R_D = 25 \text{ Km}$
3. LTE/DVB cooperation; set of TV channels:  $\text{TV}_1, \text{TV}_2, \text{TV}_3, \text{TV}_4$ ;  $R_D = 25 \text{ Km}$
4. Standalone DVB network; set of TV channels:  $\text{TV}_1, \text{TV}_2, \text{TV}_3, \text{TV}_4$  (broadcast on DVB only)

From these Nash results, we see that for the given subscription fees, LTE is not able to serve alone any set of TV channels. DVB however can serve alone the 4 most popular TV channels, but the latter will make more profit if they consider cooperation

with LTE. So in this case, the optimal mobile TV network will be obtained by the cooperation of LTE and DVB to offer the 4 most popular TV channels (channels 1, 2, 3 and 4) with a DVB radius  $R_D = 25 \text{ Km}$  (Nash equilibrium number 3). By this cooperation, LTE will be able to offer the services without increasing the fees and DVB will make more profit.

For higher LTE penetration, for example 80%, we obtain three Nash equilibria:

1. LTE/DVB cooperation; set of TV channels:  $TV_1, TV_2, TV_4, TV_5$ ;  $R_D = 25 \text{ Km}$
2. LTE/DVB cooperation; set of TV channels:  $TV_1, TV_2, TV_3, TV_5$ ;  $R_D = 25 \text{ Km}$
3. LTE/DVB cooperation; set of TV channels:  $TV_1, TV_2, TV_3, TV_4$ ;  $R_D = 25 \text{ Km}$

The Nash equilibrium number 3 is again the optimal configuration, as it brings more profits to operators.

## 4.4 Adaptation to other market scenario

We derived in the previous section general closed form equation for profit sharing under shapley distribution for two cooperative cases. In this section we consider other mobile TV deployment scenarios and show how we can adapt the general results to each specific market state. We consider four key stakeholder: MNO and its local TV contents provider, DVB operator and Pay TV channel owner. And we identify two other plausible scenarios than the already described cooperative one:

### 4.4.1 Market led by LTE

According to [65], a mobile operator could lead the initiative and build a broadcast network autonomously; assuming vertical control of the roles of broadcast network ownership and broadcast service provision.

The client ownership, in this scenario, is held by the MNO who offers mobile TV as an added value service to his clients. In other words, MNO collects the service fees from its mobile TV customers and shares them with the content creators (via the aggregator) (fig. 4-11).

Pay TV actors (like canal+ in France) are regarded as suppliers and do not have a direct billing relationship with mobile TV customers. On the other hand, the MNO

considers this new service as an additional service for his clients; this corresponds to the strategy that has classically been used by operators and that is referred as walled garden strategy. This means that MNOs develop added value services and ensure that content creators are kept well away from end-customers [76].

The DVB broadcaster is, also, used by MNO as a supplier to enhance the coverage of the network.

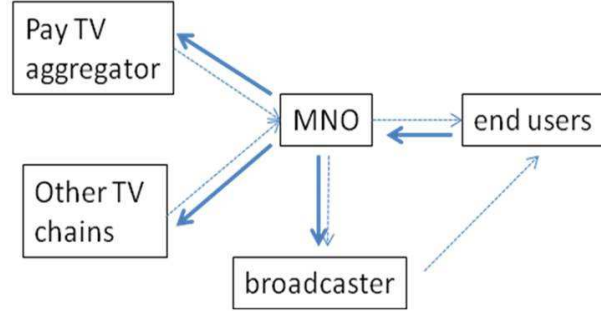


Figure 4-11: Market led by MNO scenario illustration. Plain arrows represent money flows while dashed arrows represent data flows (the physical path of TV chains from content providers to end users).

This case is a modified version of the separate LTE and DVB operator case valued in the previous section (sec. 4.3.4). It is modeled by the following adaptations:

- **Modification A:** Letting  $\mathbf{K}_{\mathbf{TV}}^{\mathbf{D}} = \emptyset$  and elimination of the DVB revenue component ( $\delta_i^D = 0$  and  $\delta_i^{coop} = \delta_i^L$ ).

*Justification:* DVB is now regarded as a supplier and does not propose a mobile TV service.

- **Modification B:** Update of the power consumption worth function by letting  $P_c(R_S, (\mathbf{e}_{i-1}^{\mathbf{D}})_{j*}) = 0$

*Justification:* There is not a coalition without LTE operator. It is the leader that proposes the TV service.

We notice that modification B leads to  $\phi_D^P(R_D, P_1, V_c^P) = \phi_L^P(R_D, P_1, V_c^P)$ . This means that the DVB operator rented as a supplier, will pay itself a given part in the total power consumption cost which is equal to that paid by LTE. One might see this to be unacceptable, however, DVB will be rewarded by an amount of money ( $-\phi_D^{bs}(R_D, P_1, V_c^{bs})$ ) paid by LTE, for renting the broadcast infrastructure in the inner region (figure 2-5) and decreasing thus, the number of required LTE base station

and their costs. With  $\phi_D^{bs}(R_D, P_1, V_c^{bs})$  is obtained by considering Eq. (4.34) and  $\mathbf{K}_{TV}^D = \emptyset$ .

Given this, we can easily prove the following proposition:

**Proposition 7** *Even though, DVB supplier will pay a share in the power consumption cost, it will gain a certain profit from its role, which can be easily proven to be always positive whenever LTE decide to use DVB to decrease the mobile TV delivery costs and increase, thus, its own profits.*

**Proof:** The DVB profit in this case is the difference between its revenue share  $-\phi_D^{bs}(R_D, P_1, V_c^{bs})$  and its cost share  $\phi_D^P(R_D, P_1, V_c^P)$ . The first part is obtained according to the balance property (eq. (4.9)) as being:

$$\begin{aligned}\phi_D^{bs}(R_D, P, V_c^{bs}) &= \phi_L^{bs}(R_D, P, V_c^{bs}) - \phi_L^{bs}(R_D, P \setminus \{L\}, V_c^{bs}) \\ &= \phi_L^{bs}(R_D, P, V_c^{bs}) - \phi_L^{bs}(R_D = 0, P \setminus \{L\}, V_c^{bs})\end{aligned}\tag{4.53}$$

So, the DVB profit is given by:

$$\begin{aligned}\phi_D(R_D, P, V) &= -\phi_D^{bs}(R_D, P, V_c^{bs}) - \phi_D^P(R_D, P_1, V_c^P) \\ &= -(\phi_L^{bs}(R_D, P, V_c^{bs}) - \phi_L^{bs}(R_D = 0, P \setminus \{L\}, V_c^{bs})) - \phi_L^P(R_D, P_1, V_c^P) \\ &= \phi_L^{bs}(R_D = 0, P \setminus \{L\}, V_c^{bs}) - (\phi_L^{bs}(R_D, P, V_c^{bs}) + \phi_L^P(R_D, P_1, V_c^P)) \\ &= \phi_L^{standalone} - \phi_L^{scenario}\end{aligned}\tag{4.54}$$

- If  $\phi_L^{standalone} \geq \phi_L^{scenario}$ , The LTE operator has the incentive to use the DVB operator as a supplier to decrease the mobile TV delivery costs, and in this case the DVB operator's profit is positive

- Otherwise, the cost in a standalone LTE network will be lower than if it rents a DVB supplier. And the profit of DVB is zero.  $\square$

#### 4.4.2 Market dominated by an alliance between DVB and Pay TV aggeragtors

In this scenario, the classical broadcast market configuration where TV chains reach their customers through the infrastructure of the DVB broadcaster is replicated to the mobile TV service. However, the classical configuration for fixed TV reception is not directly applicable, as there is a need for a direct client ownership in order to provide devices to end users. Pay TV providers are thus the best candidates to lead the market in this case as they have their established client database that can be

interested by mobile TV service. This was the case of the Paris DVB-H trial where Canal+ played a major role.

The following service design (Fig. 4-12) corresponds to this case:

- The client ownership is held by the Pay TV company who offers mobile TV as an added value service to its clients.
- The broadcaster builds the broadcast network based on its DVB technology. Note that a Pay TV company does not classically equip its clients by devices and the most plausible scenario is to offer DVB dongles that can be used with clients tablets.
- The Pay TV company continues collecting the service fees from its customers as usual, with a possibility for an additional fee for mobile TV service.

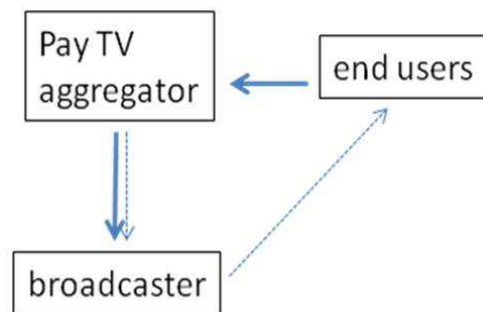


Figure 4-12: Market led by PayTV/DVB alliance scenario illustration. Plain arrows represent money flows while dashed arrows represent data flows (the physical path of TV chains from content providers to end users).

This case is similar to the joint LTE/DVB operator case developed in Section 4.3.3, with one modification to be done: eliminating the LTE network costs and revenue.

#### 4.4.3 A competitive market

In this scenario, both MNOs and Pay TV/DVB alliance build their proper networks and offer mobile TV service to their customers. The service design for each of the networks is as for scenarios 1 and 2, with the difference that the DVB broadcaster cannot be seen as a coverage supplier to the MNO in this case as it builds its own mobile TV network (Fig. 4-13) (note that there is, in general, one broadcaster in each country while several MNOs share the market).

The operators profit sharing in this case is obtained from the results of the joint LTE/DVB operator case developed in Section 4.3.3, by considering the competitive

subscribers data set given in equation (4.1), and eliminating the DVB network costs to obtain LTE operator's profits and those of LTE network costs to obtain the DVB operator's profits.

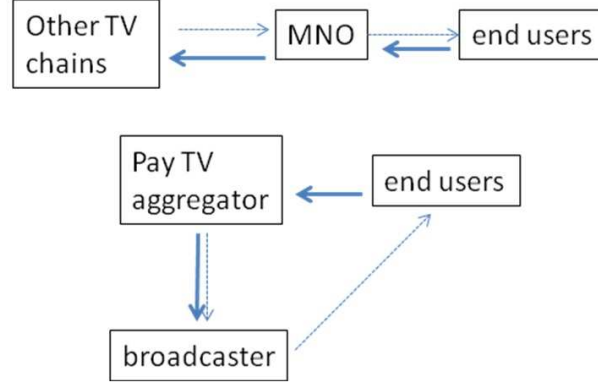


Figure 4-13: Competitive market illustration.

#### 4.4.4 Discussion and numerical results

For the sake of illustration we compare the previously introduced scenarios given the inputs given in Table 4.2:

Number of LTE subscribers	200000
Number of DVB subscribers	60000
Number of common subscribers	40000
Monthly LTE infrastructure costs $\alpha_L$ [euros/month]	833*
Total Content Costs [euros]	1800
Pay TV channels requirements [Kbps]	512 each
Local LTE TV channel requirements (other TV in figures)	$512 \times 4$ [Kbps]
subscriber fees [euros/month]	Pay TV alone:2, other TV alone: 4, Pay TV+others:6
ISD in the existent DVB system [Km]	43.31

Table 4.2: Adaptation to other market scenario: Input Parameters

We plot, then in Figure 4-14, the LTE and DVB operators' profits for different electricity prices in the already discussed market implementations.

For these particular inputs, we remark that DVB operator and Pay TV provider will always prefer to cooperate with LTE to offer mobile TV. We notice also, that in competitive market (scenario 3) the latter player will lose some of their profits if compared to the monopolist market led by DVB (scenario 2). This is due to the fact that in scenario 3 users have another choice to subscribe to (LTE service).

LTE operator, however, has the incentive to offer the TV services with the help of DVB as a supplier for low electricity price. If DVB and Pay TV players couldn't find another LTE operator, the LTE imposes this desired strategy. For higher electricity

costs, LTE and prefers the cooperation, because of the reward obtained from DVB for using the broadband lower cost infrastructure.

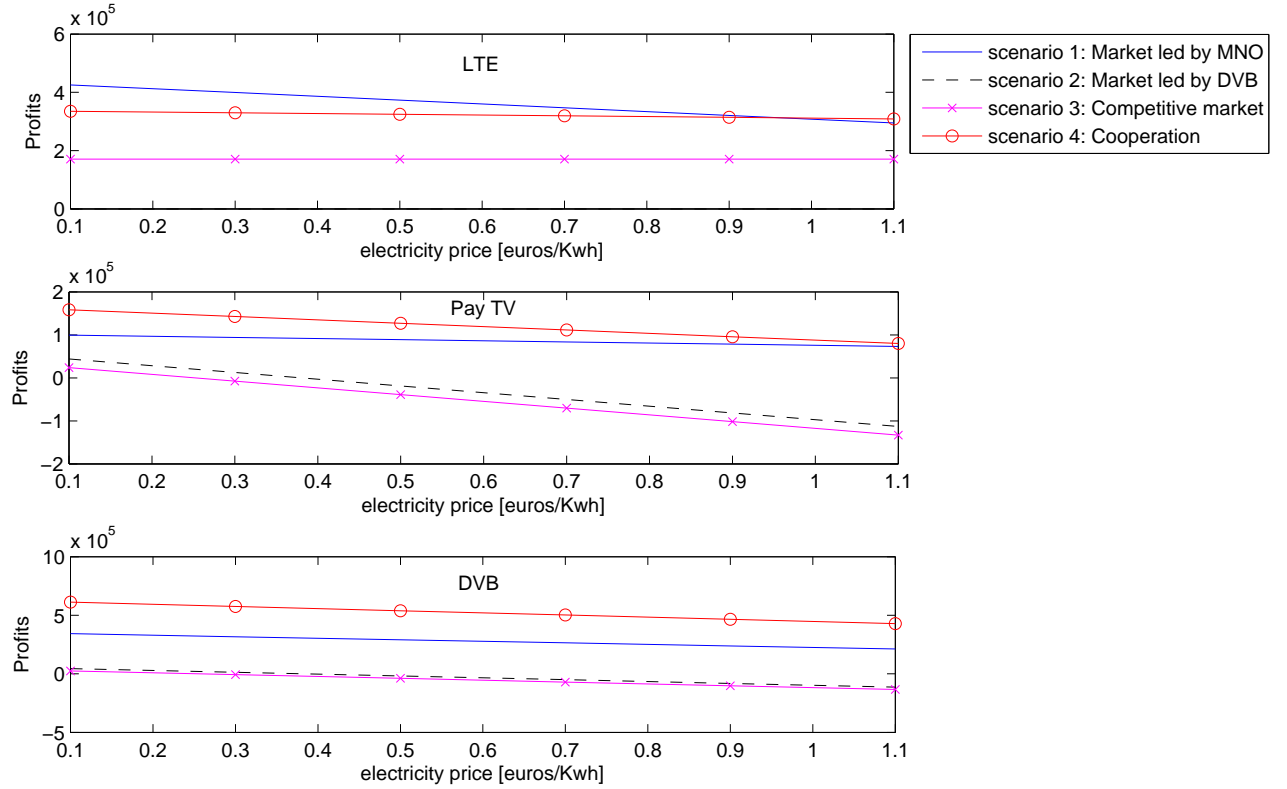


Figure 4-14: LTE and DVB operators' profits for different electricity prices

## 4.5 Conclusion

We investigated in this chapter the profit sharing of a hybrid LTE/DVB system, in cases where the operators are joint or separate. We derived close-form equations for the profit sharing between the different players in the system, namely the operators and the TV channels, using coalition games concept Shapley, and showed how this profit varies with different system parameters and market penetration rates. We eventually focused on the case where each player tries to maximize its own profit and proved that under the shapley distribution both LTE and DVB will have the incentive to cooperate when they target the same TV content and they will agree both on the same network configuration (partition of coverage area). In the same context, we obtained further the players optimal strategies at the Nash equilibrium.

The derived equations are general and can be easily adapted to fit any mobile TV market implementation to value the "fair" money flow between the different players.



However, the optimal investment decision should not be taken solely on the current market state but should also take into account its potential future changes. And this is the aim of the next chapter.

# Chapter 5

## Investment decisions in mobile TV infrastructure

The economical analysis of the previous chapter corresponds to a static case, considering one snapshot of the market state (prices and demands). We now extend this model by considering the mobile TV network deployment as a strategic investment whose value depends on the different market uncertainties and on the behavior of the main actors.

We consider a DVB centric analysis where the DVB operator, in alliance with a given pay TV provider, is the first player to enter the market. The LTE operator may follow it and enter the mobile TV market in the cooperative scenario introduced in section 2.3.2 to offer the same mobile TV service. However, the developed model is generic and can be applied to an LTE centric strategy.

The main contributions of this chapter are the following:

- We develop a real option framework for investment decision in mobile TV networks and show how broadcasters can incorporate the uncertainties related to demand and network operation costs, in this case electricity price, in their decisions.
- We develop a novel decision making framework combining the real options method with coalition game theory. We show how a decision maker can incorporate in its decision the future possibility of being joined cooperatively by another actor which may increase its profits and reduce its costs. We make use of the Shapley value to derive the profits and costs of the different actors in case of a cooperative DVB/LTE network and show how to incorporate this result in the investment decision.

- We propose a bi-level dynamic programming algorithm to solve numerically the developed real option game. The dynamic programming technique is introduced to solve the real option problem, while the strategic aspects related to game theory are tackled using the bi-level algorithm. To the best of our knowledge, this is the first time this kind of algorithms is proposed in the literature.

## 5.1 Real options background

The success of mathematical models of financial markets, starting from the Black and Scholes model in 1973 [77], has led to a large development of the usage of financial options. This tendency had an impact on capital budgeting (investment decisions) and led to the emergence of the real options theory, a term that has been first introduced by Myers in 1977 to evaluate the future opportunity to invest in uncertain environments [78]. Since then, the real options method has spread across different disciplines, ranging from natural resource investments [79], R&D projects [80], to information technology infrastructure and telecommunication equipment investments (see [81][82] for instance). For a deeper comprehension of real options theory and its applications, please refer to [83].

Unlike financial options, real investment opportunities are however rarely held by a single firm in isolation and most investment projects are open to several firms in the same industry or line of business, subject of course to the core competencies of each firm. This is not reflected in the large majority of works dealing with real options as they “*mainly consider single decision maker problems of firms operating in monopoly or perfect competition markets*” [84]. A new research field, incorporating strategic considerations in investment decisions by combining game theory with real options, is gaining in importance (see for instance [85], [86] and [87]). In the recent paper [88], the authors review two decades of real option game models and concluded that there are very few models considering cooperation between firms. This is precisely the main objective of our next contribution.

## 5.2 Uncertainties

When making the investment decision, the broadcaster has to take into account the different uncertainties impacting the project. In addition to the classical uncertainty related to the evolution of the demand (i.e., the number of customers that will pay for the service), there is an important uncertainty in DVB networks related to the electricity prices as DVB networks are highly energy consuming. The evolution of

the two random processes representing the demand level  $d_t$  and energy costs  $x_t$  are described as follows. We start with the latter.

### 5.2.1 Electricity price modeling

We consider the Geometric Ornstein-Uhlenbeck (Geometric O-U) model as it is widely used in the literature for modeling electricity prices [89]. This model assumes that the logarithm of the price follows the O-U process suitable for modeling the mean reverting behavior (the price will always return to the mean). Let  $Y_t = \log(x_t)$  denote the log of the energy price  $x_t$  at time  $t$ . It follows the mean reversion process:

$$dY_t = \alpha \cdot (\xi - Y_t) \cdot dt + \sigma \cdot dw_t \quad (5.1)$$

where  $\alpha$  is the mean reversion rate,  $\xi$  is the mean value of the logarithms of spot prices (half-hour prices of wholesale market electricity),  $\sigma$  is the volatility of the logarithms of spot prices,  $dw_t$  is the increment of a standard Wiener process.

The expected value and the variance of  $Y_t$  given the beginning state  $Y_i$  at time  $T_i$  are, respectively, given by [90]:

$$\mathbf{E}_{Y_i}[Y_t] = e^{-\alpha \cdot (t - T_i)} \cdot Y_i + \xi \cdot (1 - e^{-\alpha \cdot (t - T_i)}) \quad (5.2)$$

$$\mathbf{V}_{Y_i}[Y_t] = (1 - e^{-2\alpha \cdot (t - T_i)}) \frac{\sigma^2}{2\alpha} \quad (5.3)$$

And so, the electricity price  $x_t$  is log-normally distributed. Its mean value at time  $t$  given the initial electricity price  $x_i$  at time  $i \leq t$  is given by:

$$\begin{aligned} \mathbf{E}_{x_i}[x_t] &= e^{\mathbf{E}_{Y_i}[Y_t] + \frac{1}{2} \mathbf{V}_{Y_i}[Y_t]} \\ &= e^{e^{-\alpha \cdot (t - T_i)} \cdot \log(x_i) + \xi \cdot (1 - e^{-\alpha \cdot (t - T_i)}) + \frac{\sigma^2}{4} (1 - e^{-2\alpha \cdot (t - T_i)})} \end{aligned} \quad (5.4)$$

### 5.2.2 Demand modeling

The Geometric Brownian Motion (GBM) is a widely used model for demand in financial market. This model is however not suitable for modeling demand in almost mature markets as is the case for the telecommunication market in developed countries. We consider instead a more realistic model for the demand, developed in [91] for population evolution in large cities, whose expected value remains bounded. In this model, the demand evolves following the differential equation:

$$dd_t = \mu(t)d_t + \sigma d_t dw_t \quad (5.5)$$

where

$$\mu(t) = \frac{-\mu(1-K)e^{-\mu t}}{K + (1-K)e^{-\mu t}} \quad (5.6)$$

It is easy to prove that the mean of this latter process at time  $t$  given the beginning state  $d_i$  at time  $T_i$  is given by:

$$\mathbf{E}_{d_i}[d_t] = d_i \frac{K + (1-K)e^{-\mu_d \cdot t}}{K + (1-K)e^{-\mu_d \cdot T_i}} \quad (5.7)$$

Note that the framework developed in this paper is general and can be applied to other demand models.

## 5.3 Single decision-maker case

We focus on the case of a stand-alone DVB network where the broadcaster decides the investment date and the MNO) does not play any role. The case of a joint DVB/LTE network is studied in the next section.

### 5.3.1 Real options framework

We assume that the broadcaster can invest in the mobile TV network until a certain time denoted by  $T_D$ . This flexibility in investment opportunity over time is not considered in the classical decision method based on cost-benefit analysis (Discount Cash Flow (DCF)) [92]. The analogy between the opportunity to invest in the mobile TV project and the holding of a financial call option argues for a real options approach. In fact, the firm has the right but not the obligation to buy an asset (the project) at a future time, at an exercise price (the total cost, uncertain in our case).

We then apply this approach to answer the following question: until when is it preferable to delay the investment and how much is the value of this opportunity (option to defer)? We formulate the problem as a classical discrete-time real option problem where the aim of the decision-maker is to maximize its utility over the periods before and after the investment.

The time period is divided into epochs of length  $\delta$  (in months) and, at each time epoch  $t \in \{0, \delta, 2\delta, \dots, T_D\}$ , the broadcaster decides to invest or not based on the expected net benefit obtained from  $t$  until the obsolescence of the technology (say at  $T_{end} > T_D$ ). The profit of the operator at a given time epoch is the difference between the revenues that it gains from subscription fees and the network costs. This utility is thus equal to 0 before the investment. After the investment, it is computed using equation (5.8):

$$u(t, x_t, d_t) = (A \cdot d_t - x_t \cdot P_c(R_S)H - E_D)\delta \quad (5.8)$$

where

- $d_t$  is the demand level (number of subscribers) at time  $t$ ,
- $A$  is the per-user subscription fee,
- $P_c(R_S)$  is the power consumption necessary for covering the whole area (of radius  $R_S$ ) around the transmitter (equation (4.3)),
- $x_t$  is the energy cost at time epoch  $t$ ,
- $E_D$  is the equipment cost,
- cost parameters  $A$ ,  $H$  and  $E_D$  are given per month.

The expected aggregated discounted net profit if the operator decides to invest at time  $t$  is thus given by:

$$\begin{aligned} U(t, x_i, d_i) &= \sum_{\tau=t}^{T_{end}} \frac{\hat{u}_{(d_i, x_i)}(\tau)}{(1+r)^{(\tau-t)}} \\ &= \sum_{\tau=t}^{T_{end}} \frac{(A \cdot \mathbf{E}_{d_i}[d_\tau] - \mathbf{E}_{x_i}[x_\tau] \cdot P_c(R_S)H - E_D)\delta}{(1+r)^{(\tau-t)}} \end{aligned} \quad (5.9)$$

where  $\hat{u}_{(d_i, x_i)}(\tau)$  is the expectation of  $u(\tau, x_\tau, d_\tau)$  given the invest state  $(t, x_i, d_i)$  and  $r$  is the discount rate. Note that we discount the future cash flows using the risk free interest rate  $r$  since we assume that the projects risk can be diversified.

The value of the option at time  $t$  is thus the maximum between the expected net profit if the investment occurs at  $t$  and the value of waiting until the next epoch:

$$O(t) = \max[U(t, x_t, d_t), W(t, x_t, d_t)] \quad (5.10)$$

where the value of waiting is equal to the expected discounted value of the option at time  $t + \delta$ :

$$W(t, x_t, d_t) = \frac{E[O_{x_t, d_t}(t + \delta)]}{1+r} \quad (5.11)$$

### 5.3.2 Dynamic programming algorithm

In order to solve the above defined real option problem, we adopt a backward dynamic programming approach:

1. Discretize the demand and electricity price into discrete values  $d_k, k \in [1, N_d]$  and  $x_j, j \in [1, N_x]$ , where  $N_d$  and  $N_x$  are the number of possible values for the demand and the electricity price, respectively. Details of how to perform this discretization are given in [91] and [93]. Let  $\mathbf{s}_{k,j} = (d_k, x_j)$  be the different possible states.
2. Compute  $p(t, \mathbf{s}_{k,j}, \mathbf{s}_{k',j'})$ , the probabilities that the system moves from state  $(\mathbf{s}_{k,j})$  at time  $t$  to state  $(\mathbf{s}_{k',j'})$  at time  $t + \delta$ . As the two processes (demand and electricity price) are independent, this joint probability is simply the product of the individual probabilities of passing from  $d_k$  to  $d_{k'}$  and from  $x_j$  to  $x_{j'}$ . These latter can be found in the literature (e.g., [91, 93]). Compute also  $p_s(t, \mathbf{s}_{k,j})$ , the probabilities of being at state  $\mathbf{s}_{k,j}$  at time  $t$ , as the product of the probabilities of the electricity price being equal to  $x_j$  and the demand being equal to  $d_k$  at time  $t$ .
3. Start at the maturity date  $T_D$  at which a now or never decision should be taken. At  $t = T_D$ , the option for all state  $\mathbf{s}_{k,j}$  is calculated as:

$$O(T_D, \mathbf{s}_{k,j}) = \max[U(T_D, \mathbf{s}_{k,j}), 0] \quad (5.12)$$

4. Move back one period to  $t = T_D - \delta$  and calculate the value of waiting as:

$$W(T_D - \delta, \mathbf{s}_{k,j}) = \frac{\sum_{k',j'} p(T_D - \delta, \mathbf{s}_{k,j}, \mathbf{s}_{k',j'}) O(T_D, \mathbf{s}_{k',j'})}{(1 + r)} \quad (5.13)$$

The value of the option is thus:

$$O(T_D - \delta, \mathbf{s}_{k,j}) = \max[U(T_D - \delta, \mathbf{s}_{k,j}), W(T_D - \delta, \mathbf{s}_{k,j})] \quad (5.14)$$

5. Continue moving back until computing the value of the option at time 0.

For each system state  $\mathbf{s}_{k,j}$ , the first time  $t$  at which the value of investment is larger than the value of waiting is the optimal time to invest.

On the other side, the probability of investing at time  $t \in [0, T_D]$ , noted by  $p_{inv}(t)$  can be calculated as follow:

We first define two types of events,  $\mathbf{A}_t$  the event of investing at time  $t$  and  $\bar{\mathbf{A}}_t$  the event of not investing. The optimal time to invest is the first time at which we get the value of the discounted net profit higher than the waiting value.  $p_{inv}(t)$  is the

probability of investing at time  $t$  and not investing at any given time  $t_i \in [0, t - \delta]$ .

$$p_{inv}(t) = P(\mathbf{A}_t, \bar{\mathbf{A}}_{t-\delta}, \dots, \bar{\mathbf{A}}_0) \quad (5.15)$$

The system is a Markov chain, since that each state  $(t, x_t, d_t)$  depends only on the previous one. So,

$$p_{inv}(t) = P(\mathbf{A}_t / \bar{\mathbf{A}}_{t-\delta}) \times \prod_{i=1}^{t-\delta} P(\bar{\mathbf{A}}_{t-i} / \bar{\mathbf{A}}_{t-i-\delta}) P(\bar{\mathbf{A}}_0) \quad (5.16)$$

$P(\mathbf{A}_{t_i} / \bar{\mathbf{A}}_{t_i-\delta})$  is given by  $\frac{P(\mathbf{A}_{t_i}, \bar{\mathbf{A}}_{t_i-\delta})}{P(\bar{\mathbf{A}}_{t_i-\delta})}$  and  $P(\bar{\mathbf{A}}_{t_i} / \bar{\mathbf{A}}_{t_i-\delta})$  is given by  $\frac{P(\bar{\mathbf{A}}_{t_i}, \bar{\mathbf{A}}_{t_i-\delta})}{P(\bar{\mathbf{A}}_{t_i-\delta})}$  with

$$\begin{aligned} P(\mathbf{A}_{t_i}, \bar{\mathbf{A}}_{t_i-\delta}) &= \sum_{k,j,k',j'} p_s(t_i - \delta, \mathbf{s}_{k,j}) I_{U(t_i-\delta, \mathbf{s}_{k,j}) \leq W(t_i-\delta, \mathbf{s}_{k,j})} \\ &\quad \times p(t_i - \delta, \mathbf{s}_{k,j}, \mathbf{s}_{k',j'}) I_{U(t_i, \mathbf{s}_{k',j'}) > W(t_i, \mathbf{s}_{k',j'})} \end{aligned} \quad (5.17)$$

$$\begin{aligned} P(\bar{\mathbf{A}}_{t_i}, \bar{\mathbf{A}}_{t_i-\delta}) &= \sum_{k,j,k',j'} p_s(t_i - \delta, \mathbf{s}_{k,j}) I_{U(t_i-\delta, \mathbf{s}_{k,j}) \leq W(t_i-\delta, \mathbf{s}_{k,j})} \\ &\quad \times p(t_i - \delta, \mathbf{s}_{k,j}, \mathbf{s}_{k',j'}) I_{U(t_i, \mathbf{s}_{k',j'}) \leq W(t_i, \mathbf{s}_{k',j'})} \end{aligned} \quad (5.18)$$

with  $\delta$  is the time step,  $p_s(t, \mathbf{s}_{k,j})$  is the probability of being at state  $\mathbf{s}_{k,j}$ ,  $p(t, \mathbf{s}_{k,j}, \mathbf{s}_{k',j'})$  is the probability that the system moves from state  $(\mathbf{s}_{k,j})$  at time  $t$  to state  $(\mathbf{s}_{k',j'})$  at time  $t + \delta$  and  $I_C$  is equal to 1 if the condition  $C$  is true and 0 otherwise.

### 5.3.3 Numerical illustration

In order to illustrate the dynamic programming approach, we consider a system with the parameters of Table 5.1 (we use only parameters related to the broadcaster in this section).

	DVB	LTE
Initial cell coverage (Km)	$R_S = 25$	$R_L^u = 0.5$
Equipment cost (Euros/month)	$E_D = 0$	$E_L = 833$
Other cost parameters	$\alpha_n = 10; \beta_n = 80$	
Maturity date (months)	$T_D = 24$	$T_L = 36$
Decision epoch date (months)	$\delta = 2$	

Table 5.1: System parameters

We apply the dynamic programming approach to the broadcaster decision. Table 5.2 illustrates the decisions at a given time epoch ( $t = 18$  [months]) and for different



possible demand values and electricity prices at this instant given the initial demand value (at instant  $t = 0$ )  $D_0 = 10$  [subscribers/km<sup>2</sup>] and  $x_0 = 1.2$  [euros/month] (the complete decision table is 3-Dimensional). We observe that, for higher electricity prices, the operator prefers to wait until this price decreases unless there is certain threshold of demand level.

Electricity price	Demand level [subscribers]					
	10264	10791	11318	11845	12373	12900
0.1312	1	1	1	1	1	1
0.2005	0	0	1	1	1	1
0.3064	0	0	0	0	0	0

Table 5.2: An extraction of the decision table of the broadcaster at instant  $t = 18$  [months]. zeroes correspond to delay actions while ones correspond to immediate investment decisions.

Figure 5-1 shows the impact of the initial energy price on the average investment date. It is clear that this later increases with the initial price. In fact, low prices will not get any better in the future so the operator invests directly. However, high prices will decrease in the future since they follow a mean reversion process so it is better to postpone a little bit the investment.

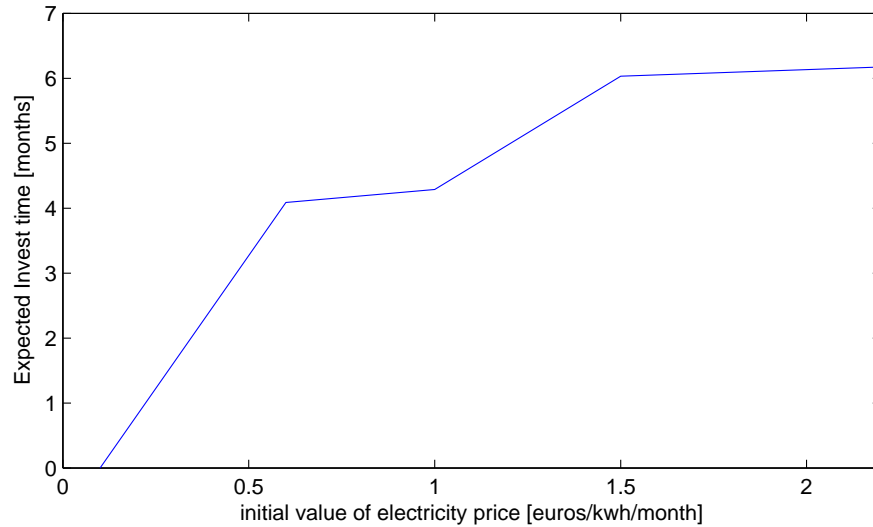


Figure 5-1: Impact of the initial energy price on the expected investment date

## 5.4 Multiple decision-maker case

In this section, we extend the real options framework developed in the previous section to account for the possibility of constructing a coalition comprising the broadcaster and the MNO. This coalition would increase the overall project profit (by bringing more customers from the MNO customer database) and reduce its costs by allowing a reduction of the DVB transmission power. We build on the profit sharing results of the static case (no timing) obtained in section 4.3.4 to define our dynamic framework where the first mover (the broadcaster) takes the first decision of investment. The MNO acts as a second mover and can decide (immediately or after some time) to join the broadcaster and forms a coalition with him if this corresponds to a win-win situation.

### 5.4.1 A game theoretical real options framework

In the dynamic framework, the broadcaster takes the first move and decides to invest in the network, but has to incorporate in its decision the possibility to be joined, immediately or later on, by the MNO. In this latter case, the MNO may increase the revenues by bringing a new set of subscribers and reduce the cost by complementing the coverage of the DVB network which will be able to reduce its transmission power. The Shapley value framework that we presented in the previous section 4.3.4 can thus be used to derive the revenue and cost share of each of the actors.

We consider three sources of uncertainty: the electricity price  $x_t$ , the number of subscribers brought by the broadcaster  $d_t^D$  and the number of subscribers brought by the MNO  $d_t^L$ . The utility of the broadcaster at time  $t$  will be equal to:

$$u_D(t, x_t, d_t^D, d_t^L) = \begin{cases} (A \cdot d_t^D - x_t \cdot P_c(R_S)H - E_D)\delta & \text{DVB only} \\ (\phi_D(d_t^D, d_t^L) - \psi_D(x_t, R_D^*))\delta & \text{cooperation} \end{cases} \quad (5.19)$$

and the utility of the MNO is computed by:

$$u_L(t, x_t, d_t^D, d_t^L) = \begin{cases} (\phi_L(d_t^D, d_t^L) - \psi_L(x_t, R_D^*))\delta & \text{cooperation} \\ 0 & \text{otherwise} \end{cases} \quad (5.20)$$

where  $R_D^*$  is the optimal coverage of the DVB transmitter. In fact we proved in section 4.3.4.3 that under the Shapley value, LTE and DVB operators offering the same TV content will have always the incentive to cooperate in offering mobile TV service and both have the same optimal configuration in terms of inner area radius ( $R_D^*$ ).  $\phi_{op}(d_t^D, d_t^L)$  and  $\psi_L(x_t, R_D^*)$  are the considered operator shares in revenue and

costs obtained by shapley value strategy (chapter 4).

Knowing that the broadcaster takes the first move and LTE follows it or not, the problem can be decoupled as two inter-related decision problems:

### Decision of the MNO

Supposing that the broadcaster decides, at time  $\tau \leq T_D$  and when the system is in state  $(d_\tau^D, d_\tau^L, x_\tau)$ , to invest in the project, the MNO has the choice to join the network immediately, to delay its decision, or to abandon the investment. This is a classical real options problem, similar to that described in section 5.3.1, but where the time origin is at  $t$  and the initial state of the market is  $(d_\tau^D, d_\tau^L, x_\tau)$ . The MNO can decide to invest until his proper maturity date  $T_L \in [\tau, T_{end}]$  and, after investment, he can exploit the project until  $T_{end}$ . The utility of the MNO at time  $t \geq \tau$  is given by equation (5.20).

For each starting state given by  $\tau$  (the broadcaster's investment date) and  $(d_\tau^D, d_\tau^L, x_\tau)$  (the market state when the broadcaster invests), the value of the option for the MNO is thus defined as in section 5.3.

### Decision of the broadcaster

Even if the broadcaster takes the first move, he must take into account the possibility of being joined later by the MNO in a coalition that may reduce its costs and increase its profits. This new source of uncertainty has to be integrated within the option's value. At each date  $\tau$  and for each state of the market  $(d_\tau^D, d_\tau^L, x_\tau)$ , the expected net profit, given by equation (5.9) in the case of a stand-alone DVB network, has thus to incorporate the future decision of the MNO:

$$U(\tau, d_\tau^D, d_\tau^L, x_\tau) = \sum_{t=\tau}^{T_{end}} \frac{\hat{u}_D(t|x_\tau, d_\tau^D, d_\tau^L)}{(1+r)^{\tau-t}} \quad (5.21)$$

where the expected utility at time  $t$  incorporates the MNO's decision:

$$\begin{aligned} \hat{u}_D(t|x_\tau, d_\tau^D, d_\tau^L) = & (A.E[d_t^D] - E[x_t].P_c(R_S)H - E_D)\delta p^L(t|\tau, d_\tau^D, d_\tau^L, x_\tau) \\ & + E[(\phi_D(d_t^D, d_t^L) - \psi_D(x_t, R_D^*))]\delta(1 - p^L(t|\tau, d_\tau^D, d_\tau^L, x_\tau)) \end{aligned} \quad (5.22)$$

where  $p^L(t|\tau, d_\tau^D, d_\tau^L, x_\tau)$  is the probability that the LTE operator did not invest at any time  $t_i \in [\tau, t]$  (It is obtained in the same logic used for eq. (5.15) by considering  $P(\bar{\mathbf{A}}_t, \bar{\mathbf{A}}_{t-1}, \dots, \bar{\mathbf{A}}_\tau)$  instead).

### 5.4.2 The bi-level dynamic programming approach

In order to solve this compound real option problem, we introduce a bi-level dynamic programming algorithm as follows:

- For each time  $\tau \in [0, T_D]$  and each system state  $s_{i,j,k} = (d_i^D, d_j^L, x_k)$ , perform a dynamic programming algorithm, like the one described in section 5.3.2, to evaluate the option of the MNO, knowing that the broadcaster decides to invest at time  $\tau$  and that the initial market state is  $s_{i,j,k}$ . Compute,  $p^L(t|\tau, d_\tau^D, d_\tau^L, x_\tau)$ , the corresponding probability that the MNO did not invest at any time  $t_i \in [\tau, t]$ , for all  $t \in [\tau, T_L]$ .
- Perform a dynamic programming algorithm to evaluate the option of the broadcaster. This algorithm has to incorporate, in the net utility of the broadcaster, the future decision of the MNO as in equation (5.21). This calculation takes as input the output of the dynamic programming algorithm relative to the decision of the MNO, introduced in the previous step.

As an output of this bi-level dynamic programming approach, the global value of the project can be computed and the expected investment times for both operators can be derived.

Note that the stochastic processes describing the evolution of the demands of DVB and LTE operators can be regarded as independent or correlated processes, but the latter assumption is more realistic as the interest of customers depends more on the offered service than on the network technology. We choose in this work a completely correlated model where the global demand is modeled as a stochastic process  $d_t$  (as the one described in section 5.2.2), and each operator has a proper demand which is proportional to its market penetration. This reduces the dimension of the problem to 2. Any other model of correlated processes can, however, be used.

### 5.4.3 Numerical illustration

The system parameters are those reported in Table 5.1. Figure 5-2 shows the expected investment dates for both operators as a function of the initial electricity price.

We observe that for low electricity price, the DVB operator will invest directly, whereas the LTE one will wait for higher electricity prices until the DVB will need him to compensate the high operation costs.

At higher initial electricity prices, the DVB operator will wait some time before investing hoping that this price decreases (due to the mean reversion nature of the process). The LTE operator will however invest at the same investment date as DVB

because the electricity price is already high and there is an immediate need for him to enter the coalition and any delay in the investment will decrease the subscription fees accumulated during the fixed project lifetime.

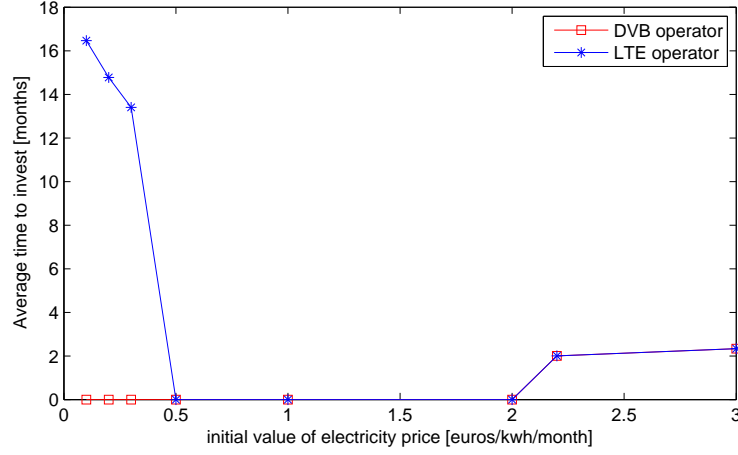


Figure 5-2: Expected investment dates for both operators function of the initial electricity price. The initial demand is fixed to 137.5 (subscriber/km<sup>2</sup>)

Figure 5-3 shows the impact of the mean reversion rate on the LTE investment date. We observe that this time decreases when the rate increases. In fact, a high mean reversion rate means that the price will return faster to the mean value, and so, if the electricity price was not favorable at this instant, it is not worthy to postpone the investment date, because the gain in the accumulated subscription revenues will compensate the high cost in this small period of time.

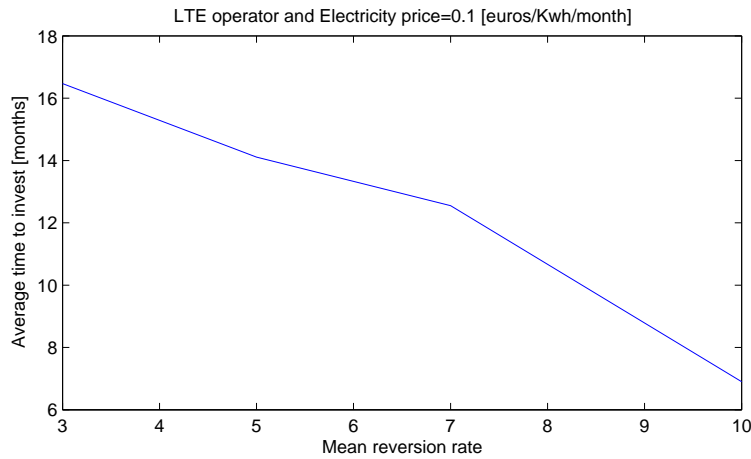


Figure 5-3: Expected investment date for the LTE operator function of the mean reversion rate

## 5.5 Conclusion

We developed, in this chapter, a framework for investment decisions in mobile TV networks, based on real options theory, and which takes into account two main sources of uncertainty related to demand and network operation cost. We considered the presence of two main actors in the offering of the mobile TV service: DVB operators who rely on their DVB towers and the DVB-T2 lite technology and mobile network operators who would use their classical cellular networks along with LTE eMBMS technology. The LTE operator would complement the DVB coverage if the two operators decide to make a coalition for delivering the mobile TV service. This is achieved through the definition of a novel game theoretical real options methodology that incorporates the possible formation of a future coalition in the investment decision of the broadcaster.

In order to solve this investment decision making problem in practice, we proposed a novel bi-level dynamic programming algorithm based on backward induction and applied it to both players. The proposed framework is flexible and applicable to different types of uncertainties and other investment problems.



# Chapter 6

## Conclusion and perspectives

### 6.1 Thesis summary

We investigated in this thesis the performance of a 3GPP/DVB hybrid cooperative network, where DVB operators who relies on their DVB towers along with DVB-T2 lite technology and mobile network operators who would use their classical cellular networks along with LTE eMBMS technology cooperate in coverage extension scenario to offer mobile TV service: DVB offers mobile TV near the broadcast tower and LTE offers it in the remainder of the network. This results in a continuation in the delivery of the Mobile TV service with lower investment costs.

In the first part of this document we specifically evaluated the users QoS in terms of quantifiable metrics, notably the probability of service degradation due to non availability of LTE bearers, its frequency and duration. Results emphasized the need of both metrics for a complete description of watching experience.

We explored then those later QoS metrics in the presence of a playout buffer at the receiver side. Our results showed the trends of these metrics as a function of several system parameters, giving thus design rules for a potential dynamic playout buffer management so as to enhance live TV watching experience. We investigated also, the possibility of unicast re-transmission in lossless channels via LTE bearer to combat video frame losses.

We note that results of this part of our work serve as a basis for DVB/LTE network dimensioning, given a target QoS.

We tackled in the second part the economic issues of this cooperative network. We defined the profit sharing between LTE and DVB operators as well as TV channels providers, taking into account the subscription revenues as well as the infrastructure and operation costs, in cases where the operators are joint or separate, using coalition games and Shapley value. The derived closed-form equations are general and can be



adapted to any market implementations with some simple modifications as we did for two other market implementation: Market led by MNO and another led by Pay TV. We coupled this profit sharing strategy with a game theory framework to define the Nash equilibrium and obtain the stable coalition to offer mobile TV.

we developed, finally, a strategic investment framework for mobile TV infrastructure, based on real options theory, taking into account two main sources of uncertainty the service demand and the network operation cost. We considered a realistic setting where the mobile TV network is mainly relying on a DVB infrastructure whose coverage can be complemented by the cellular network. We proposed first a dynamic programming algorithm for DVB-only network to take a decision whether to deploy the network or not, and if yes, when to do so, taking into account the cited uncertainties. We extended, then, this framework by a bi-level dynamic programming in order to include, in the investment decision, the reaction of the mobile network operator, which may decide to join cooperatively the broadcaster in the investment, bringing thus more customers and reducing the network cost. The proposed framework is flexible and applicable to different types of uncertainties and other investment problems.

## 6.2 Future Works

We explored in this work the LTE/DVB cooperation in a coverage extension scenario, where the service area is split between LTE and DVB operators. A direct extension would be the investigation of this cooperation in a service extension way, where the targeted service is split wisely between both operators bearers for an optimal multimedia delivery, using some interesting tools such as scalable video coding (SVC) and network coding.

On the other side, the economic study, would be extended to the case with more than two actors/coalitions. An interesting case to analyze is when several LTE operators compete for forming the coalition with the broadcaster or when several coalitions with different actors are possible.

Finally, we think that the LTE/DVB cooperation should not be limited to Mobile TV case only. It is quite interesting to explore the impact of this common telecommunication/broadcast access on the delivery of other services such as streaming and file datacasting. We aim in our future works to explore smart caching policies for LTE users aided by the DVB bearer.

We detail in the following the previously introduced research perspectives.

### **6.2.1 SVC for an efficient delivery of video services in a co-operative LTE/DVB network**

The service extension scenario is another potential way to implement the cooperative LTE/DVB network, where both DVB and LTE operators cover the total service area but split the delivered service in an intelligent way between both bearers. Instead of considering explicit load balancing strategies, redirecting traffic to the best connected network such as those done in [15–18], we aim to use more sophisticated video coding tools, namely the SVC.

SVC is an interesting scheme that is being intensively discussed in the literature [94][95]. It consists on encoding the same video stream into a Base Layer (BL) that guarantees the minimum video quality that has to be received by all the users and several Enhancement Layers (EL) for a diversified quality/temporal/resolution requirements. We aim to find an efficient control policy to adapt the video layers coding to user requirements as well as network state and schedule it wisely on LTE or DVB bearer. A special attention should be taken regarding the synchronization between the transmitted layers, as they are delivered by separate operators.

### **6.2.2 Network coding to enhance video delivery robustness**

Another strategy to combat link failure especially LTE ones is using the network coding strategy. Network coding technique provides some primary information and other backup ones and performs at the packet level. We aim to take advantage of the wireless access diversity and define a smart mixing of information at packet level by considering logical or analytic functions between packets delivered on both transmission bearer such as works done in [96][97]. These packets are combined by a certain function at the receiver side to recover, thus, potential losses.

### **6.2.3 Intelligent caching policies for streaming and datacasting in a hybrid LTE/DVB network**

Researchers of the M3 ANR project [98] suggested to have an "open broadcast access to every types of multimedia contents" [99], and not limiting mobile DVB to live TV and radio only. They introduced an interesting research direction to deliver popular non-live contents via intelligent caching strategies, namely the "predictive datacasting".

The predictive datacasting, also known as preemptive downloading, could be seen a way to offload LTE traffic (especially video on demand) on DVB bearer and

prevents thus network congestion at peak time for example. Indeed, authors in [99] claimed that broadcast bearer is able to deliver mass download of popular contents to already "profiled" on-move users to be cached and consumed latter whatever is their reception conditions.

This would be an interesting subject to evaluate in order to explore intelligent caching policies for a better on demand multimedia consumption, by choosing the optimal time, way or server to download this profiled content.

#### **6.2.4 Extension of the economic framework**

The economic framework developed in this thesis is considered a base step towards a complete business study. It defines the profit sharing strategy and the games towards an optimal investment decision. However, this latter game is limited to the case where we have a single LTE operator in the market which is not realistic, since usually we have one broadcast operator in the country and multiple broadband ones. We aim to extend the real option framework with game theory to take into consideration the presence of other competing operators that can be followers or leaders in the investment decision.

# Publications

## JOURNAL PAPERS

- [J.1] Amal Abdel Razzac, SalahEddine Elayoubi, Tijani Chahed, Bachar El Hassan, "Dimensioning and profit sharing in hybrid LTE/DVB systems to offer mobile TV services", IEEE Transactions on Wireless Communications. vol.12, no.12, pp.6314,6327, December 2013
- [J.2] Amal Abdel Razzac, SalahEddine Elayoubi, Tijani Chahed, Bachar El Hassan, Impact of playout buffering on mobile TV performance, **Submitted**
- [J.3] Amal Abdel Razzac, SalahEddine Elayoubi, Linda Salahaldin, Tijani Chahed, Yezekael Hayel, "A game theoretical real options framework for investment decisions in mobile TV infrastructure", **Submitted**

## CONFERENCE PAPERS

- [C.1] Amal Abdel Razzac, SalahEddine Elayoubi, Tijani Chahed, Bachar El Hassan, "Impact of LTE and DVB-NGH cooperation on QoS of Mobile TV users" , in IEEE International Conference on Communications, ICC 2013 , Budapest-Hungary, June 2013
- [C.2] Amal Abdel Razzac, SalahEddine Elayoubi, Tijani Chahed, Bachar El Hassan, Planning of Mobile TV service in standalone and cooperative DVB-NGH and LTE networks, in IEEE WiVid 2013, Tokyo - Japan, May 2013.
- [C.3] Amal Abdel Razzac, SalahEddine Elayoubi, Tijani Chahed, Bachar El Hassan, "Comparison of LTE eMBMS and DVB-NGH mobile TV solutions from an energy consumption perspective", Green Cellular '13 : International Workshop on End-to-End Green Cellular Networks, IEEE, 08 september 2013, London, United Kingdom, 2013

- [C.4] Amal Abdel Razzac, SalahEddine Elayoubi, Tijani Chahed, Bachar El Hassan, Practical implementation of Mobile TV delivery in cooperative LTE/DVB networks, IEEE WiVid 2014, Hammamet, Tunisia, May 2014

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# Appendices

# Appendix A

## Discretization Time Step

The discretization time step  $\tau$  should be chosen as large as possible while guaranteeing that the unicast flows state will not change between two consecutive time slots.

On the other side, the real-time unicast flows of a given class  $s$  are considered to have Poisson distributed arrival, with rate  $\lambda_s$ , and exponentially distributed service with rate  $\mu_s$ . So the holding time  $h(\mathbf{a})$  of a state  $\mathbf{a}$  is the minimal time until an arrival or departure of a flow of one of the  $S$  classes occurs. According to the superposition property of exponential events,  $h(\mathbf{a})$  will have an exponential distribution with average  $\overline{h(\mathbf{a})}$  equal to the inverse of the sum of all the event rates:

$$\overline{h(\mathbf{a})} = \frac{1}{\sum_{\forall s} \lambda_s \cdot I_{\{a_s < N_{max}^s + a_s \mu_s\}}} \quad (\text{A.1})$$

where  $N_{max}^s$  is the maximal number of potential class  $s$  unicast users and  $I_{\{C\}} = 1$  if condition C is verified and 0 otherwise.

Finally,  $\tau$  has to be the minimum between these states holding times:

$$\tau = \min(\overline{h(\mathbf{a})}) \quad \forall \mathbf{a} \quad (\text{A.2})$$





## Appendix B

# Probability distribution of beginning state of the sojourn

The goal in Section 2.4.1 is to calculate the average number of time steps spent in  $\overline{\Theta_k}$  before hitting  $\Theta_k$ . We do so by first calculating  $m_{v \rightarrow \Theta_k}$ , the number of time steps spent in  $\overline{\Theta_k}$  before hitting  $\Theta_k$  starting from state  $v$ . And then we take the average for all states  $v$  weighing by  $p(v)$  the probability of starting at state  $v$ . Calculation of the probability vector  $p$  is actually taken from reference [44]. The latter defines  $p_n$  to be the probability distribution of starting the  $\overline{\Theta_k}$  sojourn at each state  $v \in \overline{\Theta_k}$  after the  $n_{th}$  visit. This distribution is given by:

$$p_n = p_1 \cdot G^{n-1} \quad (\text{B.1})$$

We aim to calculate the metric at the stationary regime, by considering high value of  $n$ .

$p_1$  is the probability distribution to start for the first time at each state  $v \in \overline{\Theta_k}$ . It is the sum of two probabilities: probability to start immediately by a state  $v \in \overline{\Theta_k}$  and probability to start by  $v' \in \Theta_k$  and move to the state  $v \in \overline{\Theta_k}$ . And so, vector  $p_1$  is defined as follows:

$$p_1 = \alpha_{\overline{\Theta_k}} + \alpha_{\Theta_k} \cdot (\mathbf{I} - \mathbf{Q}_{\Theta_k \Theta_k})^{-1} \cdot \mathbf{Q}_{\Theta_k \overline{\Theta_k}} \quad (\text{B.2})$$

with  $\mathbf{I}$  the identity matrix,  $\mathbf{Q}_{AB}$  the transition probability matrix from states in  $A$  to  $B$  and  $\alpha_A$  the initial probabilities of states in set  $A$ . These probabilities will not affect the stationary system we are studying.

On the other hand,  $G$  is the probability to start at a given state  $v \in \overline{\Theta_k}$  then

move to state  $v' \in \Theta_{\mathbf{k}}$  and return finally to state  $v'' \in \overline{\Theta_{\mathbf{k}}}$ . It is given by:

$$G = (\mathbf{I} - \mathbf{Q}_{\overline{\Theta_{\mathbf{k}}}})^{-1} \cdot \mathbf{Q}_{\overline{\Theta_{\mathbf{k}}}\Theta_{\mathbf{k}}} \cdot (\mathbf{I} - \mathbf{Q}_{\Theta_{\mathbf{k}}\overline{\Theta_{\mathbf{k}}}})^{-1} \cdot \mathbf{Q}_{\Theta_{\mathbf{k}}\overline{\Theta_{\mathbf{k}}}} \quad (\text{B.3})$$

# Appendix C

## Equations of frame loss probability

Referring to buffer dynamics described in Section 3.2.1, we note that a given state  $v = (\mathbf{a} \in \mathbf{A}_k, 0 < b < D_b, 0)$  in the "Buffering only" phase can have anterior states from two possible phases : "Buffering only"  $v_1 = (\mathbf{a}' \in \mathbf{A}_k, b - \tau, 0)$  or "Idle" phases  $v_2 = (\mathbf{a}' \in \overline{\mathbf{A}_k}, 0, 0)$ . The loss of the last received frame  $f_\eta$  (Fig. 3-4) is due to the combination of two events : the loss of this frame and its no retransmission due to lack of resources, with probability  $\phi(\mathbf{a})$ . And hence we prove the first condition in Proposition 2 (Eqn. (3.14) and (3.16))

$$P_\eta(v) = \sum_{\forall(v_1, v_2)} \left( \Pi(v_1) \cdot q_{v_1 v} + \Pi(v_2) \cdot q_{v_2 v} \right) \cdot \phi(\mathbf{a}) = \Pi(v) \cdot \phi(\mathbf{a}) \quad (\text{C.1})$$

with  $q_{v_i v}$  the transition probability given by Eqn. (3.3) and  $\Pi$  the distribution probability given by the balance equation (3.7) of the manuscript.

However, if frame  $f_j$  with  $j \in \{1, \dots, \eta - 1\}$  is lost, this means that it has been detected as an erroneous frame at the beginning of one of the states where  $b = j \cdot \tau$  and could not be retransmitted. Since we considered that the base station will only keep track of the last sent frame, the user will only be able to ask for the retransmission of this frame. And so, frame  $f_j$  will be carried, at each time step  $n$ , as it is to the state with buffered duration  $b = (j + n) \cdot \tau$ . We can calculate the loss probabilities of each frame recursively:

$$\begin{aligned} P_j(\mathbf{a}, b, 0) = & \sum_{\forall \mathbf{a}' \in \mathbf{A}_k} \left( P_j(\mathbf{a}', b - \tau, 0) \cdot Q_b((\mathbf{a}', b - \tau, 0), (\mathbf{a}, b, 0)) \right) \\ & + \sum_{\forall \mathbf{a}' \in \overline{\mathbf{A}_k}} \left( P_j(\mathbf{a}', 0, 0) \cdot Q_b((\mathbf{a}', 0, 0), (\mathbf{a}, b, 0)) \right) \end{aligned} \quad (\text{C.2})$$

It is obvious that the anterior state will not affect the considered state  $v$  if the

former was an "Idle" one ( $b = 0$  where there are no already buffered frames). So  $P_j(\mathbf{a}', 0, 0) = 0$  and we hence obtain the first condition of Proposition 3 (Eqns. (3.18) and (3.19)).

On the other hand, a state  $v' = (\mathbf{a} \in \mathbf{A}_k, b > 0, 1)$  belonging to the "Buffering and serving" phase (or to the "Serving only" phase), can have anterior states from three possible phases (Section 3.2.1):  $v'_1 = (\mathbf{a} \in \mathbf{A}_k, b - \tau, 0)$  belonging to the "Buffering Only" phase,  $v'_2 = (\mathbf{a} \in \mathbf{A}_k, b, 1)$  from the "Buffering and serving" phase and possible state  $v'_3 = (\mathbf{a} \in \overline{\mathbf{A}_k}, b + \tau, 1)$  from the "Service only" phase.

The last received frame  $f_\eta$  is found lost if the frame  $f_{\eta+1}$  was already lost in the previous state belonging to the "Serving only" sets. It is lost with probability  $\phi(\mathbf{a})$  if the previous state was in the "Buffering and Serving" or "Buffering only" sets (it is a new pushed frame). For the former case the retransmission is not possible unless the buffer content is larger or equal to  $\frac{2}{B}$  to maintain the playing continuity. In fact, the retransmission is only beneficial if it happens before totally playing the frame prior to the lost one. On the other side, the frame is detected as a loss in an interval of  $\frac{1}{B}$  [s] and retransmitted in the next  $\frac{1}{B}$  [s]. As we are in a serving state, the player should find two existent frames to consume in these  $\frac{2}{B}$  [s] or the buffer will be empty while waiting the new or retransmitted frame and the playing will be stalled.

We obtain thus the second condition in Proposition 2 (Eqn. (3.14) and (3.16)).

Finally, and as previously explained, the other frames  $f_j$  with  $j = \{1, \dots, \eta - 1\}$  are carried from previous states. The frames indexes are translated by  $-1$  if the anterior states belong to "Buffering and service" or "Serving only" phases and carried as is if the anterior state is "Buffering only". This explains the second condition of Proposition 3 (Eqns. (3.18) and (3.19)).

# Appendix D

## Probability of frame loss and no re-transmission event

We define  $\mathbf{X}_k$  as  $L_{\mathbf{X}_k} \times U$ -matrix, where  $\mathbf{X}_k(:, u)$  represents the number of potential unicast retransmission demands from  $TV_k$  users which are at position  $u$ . Since the study is done for a specific user at position  $u$ , we should have  $1 \leq \mathbf{X}_k(l, u) \leq n_{TV}(u)$  and  $0 \leq \mathbf{X}_k(l, u') \leq n_{TV_k}(u')$  (with  $n_{TV_k}(u)$  the total number of  $TV_k$  users at position  $u$ ).

The unicast demands belonging to TV channel  $TV_k$  and represented by vector  $\mathbf{X}_k(l, :)$  are served only if we their minimum required resources while serving the real-time services  $\mathbf{a}$ , all the  $K_{TV}$  broadcast TV channels and all the retransmission demands of higher priorities TV channels  $(1, \dots, k-1)$ .

We define  $\mathbf{S}_{\mathbf{X}_k(l,:)}^{\mathbf{a}}$  as  $L' \times U \times (k-1)$  matrix whose vector  $\mathbf{S}_{\mathbf{X}_k(l,:)}^{\mathbf{a}}(i, u, :)$  corresponds to a possible combination of unicast demands from the  $k-1$  higher priority TV channels users at position  $u$  and verifying

$$n_{RB_{remaining}^{TV}}(\mathbf{a}) - \sum_{j=1}^{K_{TV}} n_{RB_{TV_j}}^{min} - \sum_{u=1}^U \left( \sum_{j=1}^{k-1} \mathbf{S}_{\mathbf{X}_k(l,:)}^{\mathbf{a}}(l', u, j) \cdot \mathbf{Y}(u, j) \right) \geq \sum_{u=1}^U \mathbf{X}_k(l, u) \cdot \mathbf{Y}(u, k) \quad (\text{D.1})$$

where  $\mathbf{Y}$  is  $U \times K_{TV}$ -matrix containing the minimal number of PRBs to be used by a unicast retransmission demands of TV channels of priorities 1 to  $K_{TV}$  (Eqn. (2.5) of the manuscript for  $d_s = d_{TV}^{min}$ ) and  $n_{RB_{remaining}^{TV}}(\mathbf{a})$  is the remaining PRBs after serving the  $S$  class flows of the state  $\mathbf{a}$  at each position  $u$ .

The probability  $P_{\mathbf{X}_k(l,:)}^s(\mathbf{a})$  of being able to serve the  $\mathbf{X}_k(l, :)$  unicast retransmission demands when the real-time flows is represented by  $\mathbf{a}$  is the sum of the probabilities of having  $(k-1)$ -tuplets represented by  $\mathbf{S}_{\mathbf{u}_k}^{\mathbf{a}}$

$$P_{\mathbf{X}_k(l,:)}^s(\mathbf{a}) = \sum_{i=1}^{L'} \prod_{u=1}^U \prod_{j=1}^{k-1} \binom{n_{TV_j}(u)}{l_{iju}} p_u^{l_{iju}} (1 - p_u)^{n_{TV_j}(u) - l_{iju}} \quad (\text{D.2})$$

where  $n_{TV_j}$  is the maximal number of users watching TV channel  $TV_j$  at position  $u$  and  $l_{iju} = S_{\mathbf{X}_k(l,:)}(i, u, j)$  is the number of users who asked for a retransmission.

The probability  $s_{\mathbf{X}_k(l,:)}$  of having  $\mathbf{X}_k(l,:)$  demands and to have the target user among them is the probability that the latter user has experienced a loss and  $u_k - 1$  users other than the considered one have detected a loss event as well:

$$\begin{aligned} s_{\mathbf{X}_k(l,:)} &= p_u \binom{n_{TV_k}(u) - 1}{\mathbf{X}_k(l, u) - 1} p_u^{\mathbf{X}_k(l, u) - 1} (1 - p_u)^{n_{TV_k}(u) - \mathbf{X}_k(l, u)} \\ &\quad \times \prod_{u'=1:u' \neq u}^U \binom{n_{TV_k}(u')}{\mathbf{X}_k(l, u')} p_{u'}^{\mathbf{X}_k(l, u')} (1 - p_{u'})^{n_{TV_k}(u') - \mathbf{X}_k(l, u')} \end{aligned} \quad (\text{D.3})$$

Finally, the probability to serve a user after a loss event is given by:

$$\sum_{l=1}^{L_{\mathbf{X}_k}} s_{\mathbf{X}_k(l,:)} \cdot P_{\mathbf{X}_k(l,:)}^s(\mathbf{a}) \quad (\text{D.4})$$

And so, the probability that a frame is not lost ( $1 - \phi(\mathbf{a})$ ) is the probability of either a loss event did not happen or a loss event occurred but the network was able to retransmit it:

$$1 - \phi(\mathbf{a}) = 1 - p_u + \sum_{l=1}^{L_{\mathbf{X}_k(l,:)}} s_{\mathbf{X}_k(l,:)} \cdot P_{\mathbf{X}_k(l,:)}^s(\mathbf{a}) \quad (\text{D.5})$$

$\phi(\mathbf{a})$  is the probability of frame loss we wish to calculate.

# Appendix E

## Derivation of profit sharing expressions under Shapley value

### Expressions (4.17)-(4.19)

The shapley value corresponding to the operator is obtained by the sum of the operator Marginal Contributions (MC) over all the possible ordering combinations (permutations) divided by the total number of those permutations (Eqn. (4.7)). We have  $N = |\mathbf{K}_{\mathbf{TV}}| + 1$  players, let  $\Pi$  the set of the  $N!$  possible permutations. An example of permutation  $\pi \in \Pi$  is represented in figure E-1:

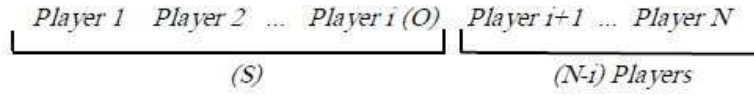


Figure E-1: Representation of a permutation

MC of the operator (denoted by  $O$  in this permutation) :  $\Delta_o(V, S(\pi, o))$ , is the difference between the worth function  $V(S)$  of coalition  $(S)$  containing players of order 1 till  $i$  and the worth function  $V(S \setminus \{i\})$  of the coalition of players from order 1 to  $i - 1$ .

For each network configuration  $R_D$  and the set of TV channels  $\mathbf{k}_{\mathbf{TV}}$  in  $(S)$ , the worth function  $V(S)$  is the power cost in Eqn. (4.17), and is given by:  $\alpha_e \cdot H \cdot P_c(R_D, \mathbf{k}_{\mathbf{TV}}) I_{\{operator \in (S)\}}$ . It is the infrastructure costs in Eqn. (4.18)) and is given by  $C_L(R_D, \mathbf{k}_{\mathbf{TV}}) I_{\{operator \in (S)\}}$ . And finally it is the equipment costs in Eq. (4.19)) ( $V_c^{rent}(R_D, S) = C_D^{rent} I_{\{operator \in (S)\}}$ ). It is clear that those latter worth functions are null if the operator is not in the coalition, and this means that  $V(S \setminus \{i\}) = 0$  and finally  $\Delta_o(V, S(\pi, o)) = V(S)$ .



Then, we have to sum over all possible permutations. To ease the computation of this sum, we divide the permutations set  $\Pi$  into  $N$  set of ordering  $\Pi_i$  where  $i \in (1, \dots, N)$ . We define  $\Pi_i$  as being the set of all possible ordered combinations of players where the operator is the  $i^{th}$  player.

For each permutation in the ordering set  $\Pi_i$  represented by Figure 13 :

- The coalition ( $S$ ) is a combination of  $(i-1)$  TV channels chosen from the  $(N-1)$  ones and the operator. So we can have  $m_{i-1} = \binom{N-1}{i-1}$  different sets of  $i-1$  TV channels and thus  $m_{i-1}$  different coalitions ( $S_j$ ) with  $j = \{1, \dots, m_{i-1}\}$ . Let the worth function  $V(S_j)$  be the cost to serve a particular set of  $(i-1)$  TV channels chosen from the  $m_{i-1}$  possible sets.

- The order of TV channels in the coalition is taken into account, and so, using the permutation theory, each coalition ( $S_j$ ) is repeated  $(i-1)!$  times.

- each coalition ( $S_j$ ) is also repeated  $(N-i)!$  times by permuting the  $(N-i)$  other players.

So, the sum of the operator marginal cost, in a given ordering  $\Pi_i$  is given by:

$$(i-1)! \sum_{j=1}^{m_{i-1}} V(S_j) (N-i)! \quad (\text{E.1})$$

We sum this latter over all orderings and divide it by the total number of permutations ( $N!$ ) (Eqn. (4.7)):

$$\phi_o(R_D, V) = \frac{\sum_{i=2}^N (i-1)! \left( \sum_{j=1}^{m_{i-1}} V(S_j) \right) (N-i)!}{N!} \quad (\text{E.2})$$

We note that for  $i = 1$ ,  $V(S_j) = 0 \forall j \in \{1, \dots, m_{i-1}\}$ , since in this case coalition ( $S_j$ ) contains only the operator. And so, there is not any TV channel to deliver and thus there is not any cost.

We recall that  $V(S_j)$  is  $\alpha_e \cdot H \cdot P_c(R_D, S_j)$  in Eqn. (4.17) and  $C_L(R_D, S_j)$  in (4.17). To ease further the computation, we memorize the  $m_{i-1}$  coalitions ( $S_j$ ), representing the combination of  $i-1$  TV channels, in a matrix denoted by  $\mathbf{e}_{i-1}$ . It is a  $(m_{i-1} \times |\mathbf{K}_{\mathbf{TV}}|)$  matrix. Each column  $k$  in this matrix corresponds to channel  $k$  in the set  $\mathbf{K}_{\mathbf{TV}}$ . Each  $j^{th}$  line  $(\mathbf{e}_{i-1})_{j*}$  in this matrix represents a different combination of  $i-1$  served TV channels (so it is  $S_j$ ). We denote  $(e_{i-1})_{jk} = 1$  if TV channel  $k$  is to be served and zero otherwise. However,  $V(S_j) = C_D^{rent}, \forall(S_j)$  and thus simplifications in Eqn. (E.2) will lead to Eqn. (4.19).

## Expressions (4.28)-(4.34)

We consider now the case of separate operators. we have  $N_1 = K + 2$  players with  $K = |\mathbf{K}_{\mathbf{TV}}^L| + |\mathbf{K}_{\mathbf{TV}}^D| - |\mathbf{K}_{\mathbf{TV}}^{\text{com}}|$ . We reason as previously on the  $N_1!$  permutations.

We begin by the share of the DVB operator (denoted by D) in the power cost (Eqn. (4.28)). For each ordering  $\pi$  (Fig. E-1), the DVB operator marginal contribution (MC) is given by:

$$\Delta_D(V, S(\pi, D)) = \begin{cases} \alpha_e \cdot P(R_D, \mathbf{k}_{\mathbf{TV}}) \cdot H & \text{if } L \in (S \setminus \{i\}) \\ \alpha_e \cdot P(R_S, \mathbf{k}_{\mathbf{TV}}^D) \cdot H & \text{if } L \notin (S \setminus \{i\}) \end{cases} \quad (\text{E.3})$$

with  $\mathbf{k}_{\mathbf{TV}}$  is the set of TV channels in the coalition  $(S \setminus \{i\})$  (fig. E-1) and served in the cooperative case. However,  $\mathbf{k}_{\mathbf{TV}}^D$  is the set of TV channels in coalition  $(S \setminus \{i\})$  and taken from the set of TV channels served in a standalone DVB network  $\mathbf{K}_{\mathbf{TV}}^D$ . To get the sum of these MC over all possible permutations, we reason as we did in the previous section of this Appendix (B.1), by dividing the total set of permutation  $\Pi$  into  $N_1$  sets where each set  $\Pi_i$  contains the different permutations in which the DVB operator is the  $i^{\text{th}}$  player. However in this case, each set  $\Pi_i$  can be also grouped into two subsets:  $\Pi_i^1$  containing the permutations with the LTE operator is in coalition  $(S \setminus \{i\})$  and  $\Pi_i^2$  containing the other permutations of  $\Pi_i$ . The sum of the MC of each ordering set  $\Pi_i$  is thus composed of two parts:

-Part 1: Sum of MC of  $\Pi_i^1$ :

- Coalition  $(S)$  is a combination of  $(i - 2)$  TV channels chosen from the  $(N_1 - 2)$  ones, and the LTE and DVB operators. So we can have  $m_{i-2} = \binom{N_1-2}{i-2}$  different sets of  $i - 2$  TV channels and thus  $m_{i-2}$  different coalitions  $(S)$ . Let the worth function  $V(S_j)$  be the cost to serve a particular set of  $(i - 2)$  TV channels chosen from the  $m_{i-2}$  possible sets ( $j = \{1, \dots, m_{i-2}\}$ ).
- Taking into account the  $(i - 2)!$  permutation of the TV channels in  $(S_j)$ , without forgetting that the LTE operator can take any order from 1 to  $i - 1$ , we will have  $(i - 1) \cdot (i - 2)!$  coalitions with the same worth function  $V(S_j)$ . However, each ordered coalition is repeated  $(N_1 - i)!$  times (permutation of the  $(N_1 - i)$  other players).

And so, the sum of the MC in the set  $\Pi_i^1$  is given by:

$$(i - 1)(i - 2)! \left( \sum_{j=1}^{m_{i-1}} P(R_D, S_j) \right) (N_1 - i) \quad (\text{E.4})$$

We note that this sum is null for ordering 1 and 2 since in this cases coalition  $(S \setminus \{i\})$  will only contain the DVB operator for  $i = 1$  and the LTE and DVB operators for  $i = 2$  (no TV channels, no costs).

-Part 2: Sum of MC of  $\Pi_i^2$ :

Coalition (S) in this case is an ordered combination of only  $(i - 1)$  TV channels from the set  $\mathbf{K}_{\mathbf{TV}}^{\mathbf{D}}$  and the DVB operator. So the sum is obtained by the same reasoning of Eqn. (E.1), we only replace  $N$  by  $N_1$  and  $R_D$  by  $R_S$  because in this case the DVB operator is alone in the operating coalition and has to serve the total service area. We note that  $\Pi_i^2$  exists for  $i < N_1 - 1$ . And the sum of its MC is equal to zero for  $i = 1$ , because in this latter ordering, (S) contains only the DVB operator without any TV channel.

By summing those two parts over the  $N_1!$  permutations, we obtain the DVB share in the power cost:

$$\begin{aligned} \phi_D^P(R_D, P_1, V_c^P) = & \alpha_e \cdot H \frac{\sum_{i'=3}^{N_1} (i' - 1)(i' - 2)! \left( \sum_{j=1}^{m_{i'-2}} P(R_D, S_j) \right) (N_1 - i')!}{N_1!} \\ & + \alpha_e \cdot H \frac{\sum_{i=2}^{N_1-1} (i - 1)! \left( \sum_{j=1}^{m_{i-1}^D} P_c(R_S, S_j^D) \right) (N_1 - i)!}{N_1!} \end{aligned} \quad (\text{E.5})$$

Finally, we obtain equation (4.28), by replacing  $i'$  by  $i = i' - 1$ , and  $S_j$  by the line  $(\mathbf{e}_{i-1})_{j*}$  of the previously defined matrix  $\mathbf{e}_{i-1}$  (first section of appendix E) and eventually  $S_j^D$  by the line  $(\mathbf{e}_{i-1}^{\mathbf{D}})_{j*}$  of the new matrix  $\mathbf{e}_{i-1}^{\mathbf{D}}$  containing only the TV channels that can be served in the standalone DVB network.

On the other hand, the LTE share in the power costs Eqn. 4.29 is obtained in terms of the DVB share by the balance property (4.9):

$$\begin{aligned} \phi_L^P(R_D, P_1, V_c'^P) = & \phi_D^P(R_D, P_1, V_c'^P) \\ & - \phi_D^P(R_S, P_1 \setminus \{L\}, V_c') \end{aligned} \quad (\text{E.6})$$

with  $\phi_D^P(R_S, P_1 \setminus \{L\}, V_c')$  is the DVB power cost share when it serves alone the Mobile TV service. It can be obtained by replacing  $N$  by  $N_1 - 1$  in Eqn. (E.2).

After the subtraction, we obtain Eqn. (4.29).

By replacing the consumed power cost  $\alpha_e \cdot H \cdot P_c(R, S_j)$  in the previously developed equations with the LTE infrastructure cost  $C_L(R, S_j)$  we obtain the LTE share in the latter costs (Eqn. (4.33)) and then, by the balance property, we obtain the share of the DVB operator Eqn. (4.34).