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# Modeling the correlation between the energy consumption and the end-to-end traffic of services in large telecommunication networks

Wilfried Yoro

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**PhD school:** Computer science, Telecommunications, Electronics of Paris

**Defended by**

Wilfried YORO

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PhD of TELECOM SUDPARIS**

Modeling the correlation between the energy consumption and the end-to-end traffic of services in large telecommunication networks

**Defended on** 08 March 2018

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Education is the most powerful  
weapon which you can use to  
change the world.

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Nelson Mandela

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## Abstract

Internet traffic is growing exponentially. According to Cisco, mobile data traffic will increase sevenfold between 2016 and 2021, growing at a compound annual growth rate (CAGR) of 47%. In order to improve or keep up with users quality of experience (QoE), mobile carriers upgrade the network with additional equipment. As a consequence, the network carbon footprint increases over time, alongside with its energy consumption. In addition, mobile carriers margins are decreasing. Global telecommunication revenues declined by 4% between 2014 and 2015 based on the international telecommunication union (ITU) figures. These concerns fostered a great interest in the research community for reducing networks energy consumption. In this regard, many works in the literature investigate the energy consumed by services on network equipment for optimization purposes notably, focusing on the variable component of energy consumption. Energy consumption of a network equipment is composed of a variable and a fixed components. The variable component is consumed to serve traffic. The fixed component is consumed irrespective of traffic. In this thesis, our objective is to share the responsibility of service categories in the fixed energy consumption. To do so, we use the Shapley value.

First, we consider a radio access network and share the responsibility of the service categories it delivers in the fixed energy consumption. The services are classified into five categories, namely, Streaming, Web, Download, Voice and other data services. In addition, we consider the case when some service categories are mandatory to be provided, such as Voice due to legal constraints for instance. Because the Shapley value has a huge computational complexity, we introduce closed-form expressions in order to significantly reduce it.

Next, we consider the end-to-end network and all its segments, that is, the mobile access, the fixed access, the collect, the mobile core, the registers, the IP core and the service platforms. For each segment, we share the responsibility of the service categories in the fixed energy consumption with the Shapley-based model introduced in the preceding chapter. We find that Streaming is the service that consumes the most whatever the network segment, except for registers, as it represents the vast majority of Internet traffic.

Eventually, we focus on the service categories energy efficiency. First, we consider a base station and compute the services energy efficiency for the cases with and without sleep mode. Then, we consider a radio access network and compute the services energy efficiency with and without a mandatory player. Moreover, we discuss the conditions to not deteriorate the network energy efficiency over time following different upgrade scenarios.

## Résumé

D'après Cisco, le trafic mobile de données augmentera d'un facteur 7 entre 2016 et 2021. Pour faire face à l'augmentation du trafic, les opérateurs mobile dimensionnent le réseau, ce qui s'accompagne d'une augmentation de sa consommation d'énergie et de son empreinte Carbonne. En outre, les marges financières des opérateurs baissent. Ainsi, le revenu global généré par le secteur des télécommunications a connu une baisse de 4% entre 2014 et 2015 d'après l'union internationale des télécommunications (UIT). Ces préoccupations ont suscité l'intérêt de la communauté scientifique pour la réduction de la consommation électrique des réseaux. Des études dans la littérature estiment l'énergie consommée par les services sur les équipements réseaux en se focalisant sur la consommation variable. La consommation énergétique d'un équipement réseau est composée d'une composante fixe et d'une composante variable. Dans cette thèse, nous partageons la responsabilité des catégories de service dans la consommation fixe du réseau en utilisant la valeur de Shapley.

Dans un premier temps, nous considérons un réseau d'accès mobile et partageons la responsabilité des catégories de service qu'il fournit dans la consommation fixe. Nous définissons 5 catégories de service, à savoir, le « Streaming », le Web, le téléchargement, la voix et les autres services de données. En outre, nous traitons le cas de figure où certaines catégories de service sont obligatoires. Etant donné la complexité algorithmique de la valeur de Shapley, nous en proposons une forme approchée qui permet d'en réduire considérablement le temps de calcul.

Ensuite, nous considérons le réseau de bout-en-bout, c'est-à-dire, l'accès mobile, l'accès fixe, la collecte, le cœur IP, le cœur mobile, les registres et les plateformes de service. Pour chaque segment, nous partageons la responsabilité des catégories de service dans la consommation fixe en appliquant notre modèle de partage basé sur la valeur de Shapley. L'analyse des résultats montre que le service « Streaming » consomme le plus d'énergie quel que soit le segment de réseau considéré, à l'exception des registres.

Pour finir, nous traitons de la modélisation de l'efficacité énergétique des catégories de service. Dans un premier temps, nous calculons l'efficacité énergétique des catégories de service étant donné une station de base avec et sans « sleep mode ». Ensuite, nous calculons l'efficacité énergétique des catégories de service étant donné un réseau d'accès mobile et considérant les cas avec et sans catégories de service obligatoires. Aussi étudions-nous les conditions pour ne pas détériorer l'efficacité énergétique du réseau au cours du temps en fonction des scénarios de dimensionnement.



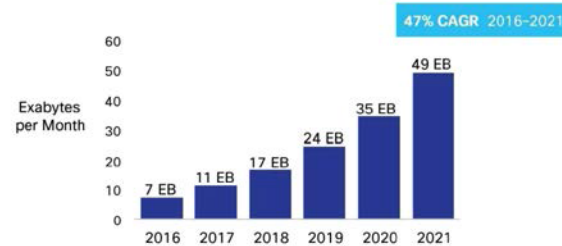
# Chapter 1

## Introduction

### 1.1 Context

According to Cisco visual networking index (VNI) 2017 [1], global mobile data traffic grew 63% in 2016, as compared to 2015 figures. Mobile data traffic has grown 18-fold over the past 5 years. Almost half a billion mobile devices and connections were added in 2016. Smartphones accounted for most of that growth. Mobile network (cellular) connection speeds grew more than 3-fold in 2016. Mobile video traffic accounted for 60% of total mobile data traffic in 2016. Average smartphone usage grew 38% in 2016.

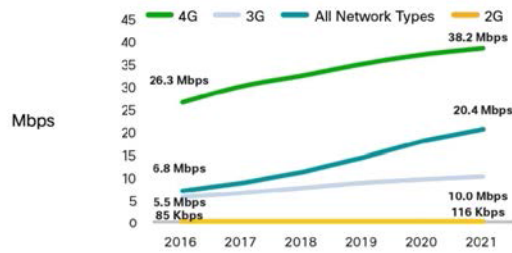
Global mobile data traffic will increase sevenfold between 2016 and 2021, growing at a compound annual growth rate (CAGR) of 47 percent, Fig. 1.1. Mobile network connection speeds will increase threefold by 2021, Fig. 1.2. Mobile video will increase 9-fold between 2016 and 2021, accounting for 78% of total mobile data traffic by the end of 2021, Fig. 1.3. Global mobile devices and connections CAGR will be 8% on the same period, Fig. 1.4.



Source: Cisco VNI Mobile, 2017

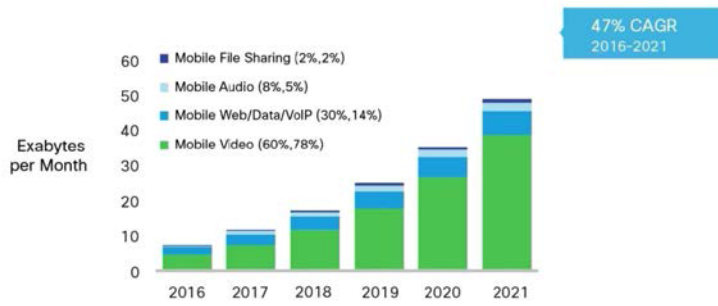
Figure 1.1: Mobile data traffic from 2016 to 2021

According to the international telecommunication union (ITU), information and communication technologies (ICTs) have been estimated to currently contribute 2% to 2.5% on the global greenhouse gas (GHG) emissions. This share is expected to increase rapidly with business as usual due to the exponential increase of internet traffic [2, 3]. International Internet bandwidth grew worldwide by 32% between 2015 and 2016, Fig. 1.5.



Source: Cisco VNI Mobile, 2017; Ookla Speedtest.net

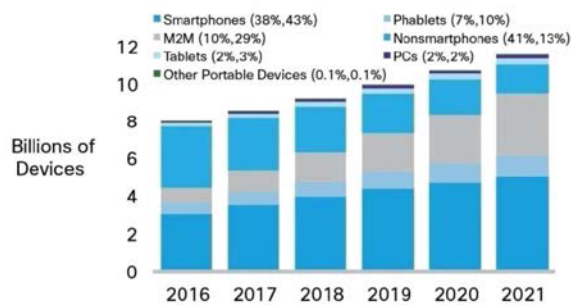
Figure 1.2: Mobile Speeds by Technology: 2G Versus 3G Versus 4G from 2016 to 2021



**Note:** Figures in parentheses refer to 2016 and 2021 traffic share.

Source: Cisco VNI Mobile, 2017

Figure 1.3: Mobile video traffic from 2016 to 2021



**Note:** Figures in parentheses refer to 2016, 2021 device share.

Source: Cisco VNI Mobile, 2017

Figure 1.4: Global mobile devices and connections growth from 2016 to 2021

Furthermore, electricity consumption of the ICT-sector is on the rise, Fig.



1.6. Meanwhile, global telecommunication revenues declined by 4% between 2014 and 2015, Fig. 1.7.

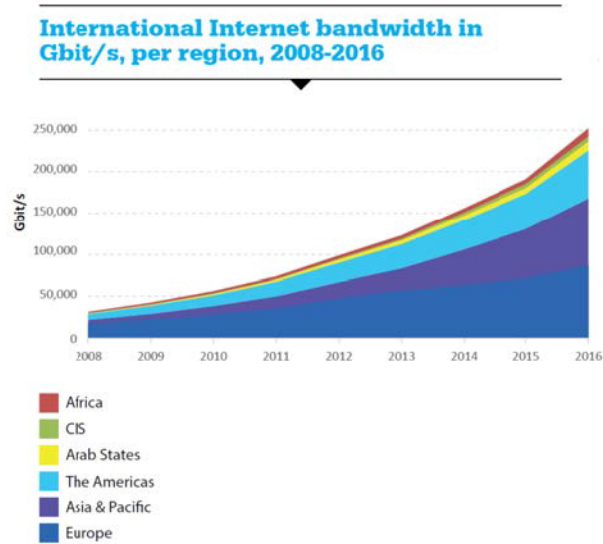


Figure 1.5: International Internet bandwidth per region from 2008 to 2016, source ITU

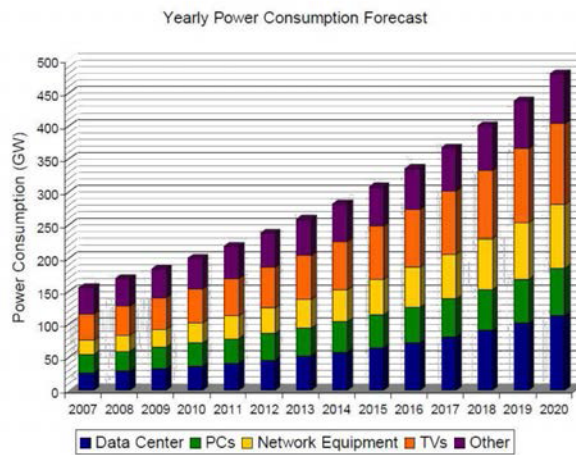


Figure 1.6: Yearly power consumption forecast from 2007 to 2020, source ITU

Many works in the literature addressed the issue of energy consumption in networks in general and in mobile networks in particular [4, 5, 6, 7, 8, 9]. It has been shown that the most power consuming part of the network is the radio access including base transceiver stations. Models have also been given to assess the power consumption of a mobile access network at country level. We can also find more fined-grained power consumption models which focus on the component level, e.g., power amplifier and cooling equipment. Moreover, the power

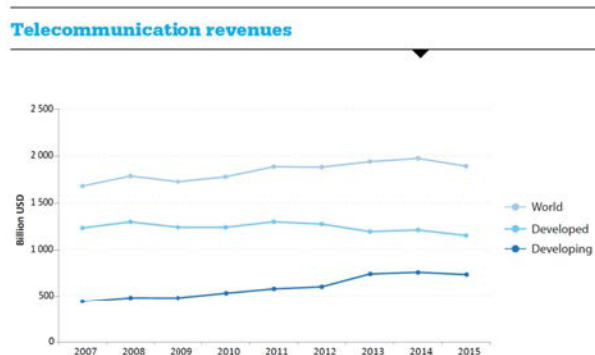


Figure 1.7: Telecommunication revenues, world and by level of development from 2007 to 2015, source ITU

consumption of micro base stations is studied in the context of heterogeneous networks.

Fewer works considered energy consumption of the services transported by the network [10, 11, 12, 13, 14]. It has been shown that it is not always energy-wise to use the Cloud; performing certain tasks locally can be more energy-efficient. The energy consumption of information and communication technology services and CO2 emission at life-cycle of equipment is also discussed in terms of negative and positive impacts: positive impact refers to potential gains due to dematerialization, such as physical transport substitution. Negative impact refers to CO2 emissions notably.

In [15, 16, 17, 18, 19, 20], the authors assess the energy consumption of services on mobile devices. They provide models useful to developers and help them to understand application energy consumption behavior. It is showed that 3G and GSM interfaces consume more energy than WiFi, which advocates for the deployment of WiFi in Heterogeneous networks. In addition, it results from these investigations that free applications consume significant energy consumption due notably to third-party advertisement modules. Moreover, it is showed that energy consumed for signaling traffic can represent a large part in the energy consumption, notably for always-on applications which send keep-alive signals on a continuous basis.

## 1.2 Motivation and methodology

Based on field measurements, the power consumption of a network equipment can be modeled as a linear function of the load as illustrated in Fig. 1.8. It consists of two components: a variable component which is consumed to serve traffic, and a fixed component consumed irrespective of traffic. As a network equipment is a common resource typically shared by several services, it is worth to determine the part of each service in the overall equipment energy consumption for optimization or eco-design purposes for example. Most authors assign to each service a share in the variable energy consumption equal to its traffic proportion as this energy component is load-dependent [10, 11]. The fixed energy consumption is not assigned to services as it is consumed irrespective of

traffic.

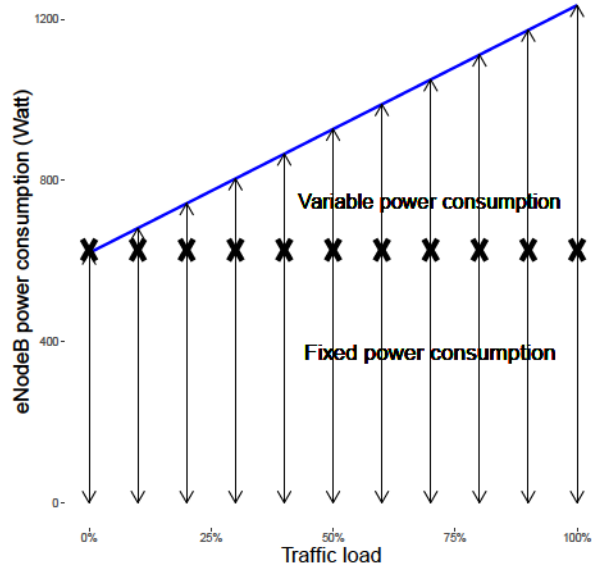


Figure 1.8: Example of power consumption of a 4G base station.

In this thesis, our objective is to share the responsibility of service categories in the fixed energy consumption, knowing that it can represent up to 80% of the total energy consumption. It may seem intuitive to assign the fixed energy consumption equally to the service categories as it is consumed irrespective of traffic. However, this energy component increases with traffic over time due to network upgrade operations as depicted in Fig. 1.9, and so, it is somehow related to services. Because of this, we propose to assign to each service category a share of the fixed energy consumption based on its impact on this increase.

We consider that the service categories cooperate to use the network as the fixed energy consumption gets amortized with traffic. Cooperation behaviors among different players, in our case service categories, are studied under the framework of cooperative game theory. In cooperative games, a solution concept is a function that allows to share a common cost or revenue among different players. The share of a player is called its payoff, and the vector of payoffs is an allocation. Some solution concepts focus on allocations which stabilize the grand coalition, that is, the coalition of all the players, and are such that no subset of players can improve its payoff by leaving the grand coalition. Some other solution concepts deal with allocations having some "fairness" properties. We assume in our case that the service categories cannot form coalitions in the network, and so, only the grand coalition can be formed. Therefore, there is no need for studying the stability of the grand coalition. We propose instead to use the Shapley value because of its "fairness" property axiomatically defined by L. Shapley as one that satisfies the following properties [21, 22, 23]: i. Symmetry: only the role of a player in the game should matter, not his specific names or label; ii. Carrier: only players contributing to the cost should be allocated a non-zero share; and iii. Linearity: the Shapley value is a linear function.

In this sense, the fairness property of the Shapley value is not a fairness measure such as the ones belonging to  $\alpha$ -fairness [24, 25, 26, 27] or yet the Jain’s fairness index [28, 29].

It is a good outcome that our model satisfies the axioms of the Shapley value as these axioms convey rational fairness properties.

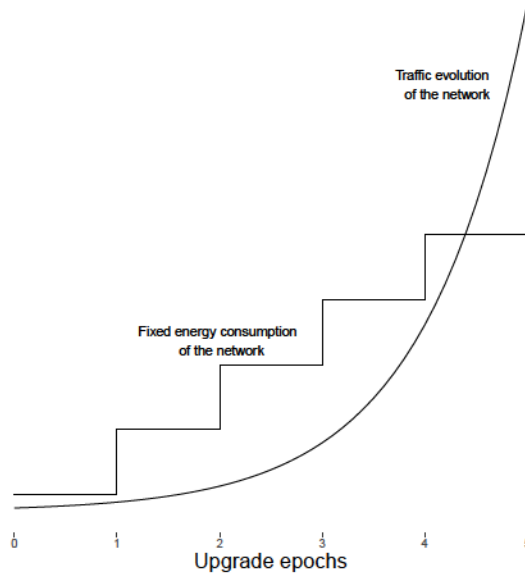


Figure 1.9: Evolution of the load and network infrastructure.

An appreciable outcome of our Shapley-based model is that it is a trade-off between an equal sharing (uniform sharing) and a sharing assigning to each service category a share equal to its traffic proportion (proportional sharing). A uniform sharing favors service categories having a large traffic, and a proportional sharing favors those having a small traffic.

Then, we derive the energy efficiency of service categories based on the output of our Shapley-based model.

The proposed models are validated with real data sets taken from an operational European network.

### 1.3 Contributions and manuscript organization

In chapter 2, we share the responsibility of service categories in the fixed energy consumption of a radio access network with the Shapley value. We consider the case when some service categories are mandatory to be provided. Taking into account the mandatory nature of a service category in the Shapley-based model increases its share as compared to the case when it is not considered to be mandatory. Because the Shapley value is of huge computational complexity, we introduce closed-form expressions which significantly reduce the computational complexity while being specific to the proposed model. Moreover, we study the case of heterogeneous networks with upgrade operations over time.

Then, in chapter 3, we consider the end-to-end network and all its segments, that is, the mobile access, the fixed access, the collect, the mobile core, the registers, the IP core and the service platforms. For each segment, we share the responsibility of the service categories in the fixed energy consumption with the Shapley-based model introduced in the preceding chapter. We apply our Shapley-based model to traffic, to so-called useful outputs (according to ETSI [30], the useful output of an equipment is defined as its maximum capacity, and is expressed as the number of Erlangs, packets/s, subscribers, or simultaneously attached users) and to both of them. The last two cases impact only the shares in the mobile core energy consumption compared with the first case. We find that Streaming is the service that consumes the most whatever the network segment, except for registers, as it represents the vast majority of Internet traffic.

Next, in chapter 4, we derive the energy efficiency of the service categories. According to the European telecommunications standards institute's (ETSI) [31], the energy efficiency of a mobile access equipment is defined to be the ratio of its traffic volume to its energy consumption. We extend this definition and define the energy efficiency of a service category to be the ratio of its traffic volume to its energy consumption. We consider first a base station. Considering the mean traffic throughput and mean power consumption, we expressed the energy efficiency of a service category as the ratio of its traffic throughput to its power consumption. We share the responsibility of the service categories in the equipment fixed power consumption using our Shapley-based model. Afterward, we study the case when the base station is put into sleep mode during idle periods. We introduce the analytical expression of the equipment power consumption in this scenario and assign it to the service categories using a new Shapley-based model consistent with this expression. In addition, we consider a radio access network and compute the energy efficiency of the service categories it delivers. We consider the case when no service category is mandatory, and the case when some service categories are mandatory. Moreover, we discuss the conditions to not deteriorate a network energy efficiency over time. We consider the case when the network is upgraded with the same radio technology, and the case when it is upgraded with a new radio technology, typically more energy and spectral efficient.

Eventually, chapter 5 concludes the manuscript and gives some hints on future work perspectives.



## Chapter 2

# Sharing the Responsibility of Service Categories in the Fixed Energy Consumption of a Radio Access Network

### 2.1 Context and problem statement

In this chapter, we consider a radio access network and share the responsibility of the service categories it delivers in the fixed energy consumption. We classify the services into categories based on criteria such as traffic, originating service providers and/or devices. Based on traffic, we segment the services into 5 categories, namely, Streaming, Web, Download, other data services and Voice.

We consider two settings: the first one with a constant network infrastructure and the other one with an evolving infrastructure, over a larger time scale, in terms of additional and/or changing equipment so as to keep up with traffic load increase.

We study two variants of the sharing model: one where no service category is mandatory and another one with mandatory player(s) which reflects the realistic case when some operators may be legally mandated by the state to offer a certain service, such as Voice.

The remainder of this chapter is organized as follows. In section 2.2, we review some literature related to cost sharing. In section 2.3, we introduce our methodology for assigning a share of the fixed energy consumption to each service category. In section 2.4, we give some material on the Shapley value concept. In section 2.5, we propose a model for assigning a share of the fixed energy consumption to each service category with the Shapley value, considering different scenarios. We discuss some implementation issues of the Shapley-based model and how we tackle these issues in section 2.6. In section 2.7, we run numerical applications based on our Shapley-based proposal, on a real data set taken from an operational European network transporting three main data services: Streaming, Web and Download, in addition to Voice and other data services. Eventually, section 2.8 concludes the chapter.

## 2.2 Related work

In [32, 33, 34, 35, 36, 37, 38], the authors discuss cost sharing in a job scheduling problem using the Shapley value. They however do not distinguish between the variable and fixed cost components, as opposed to our work where we focus on the fixed energy component. For instance, Mishra et al. [32] consider a set of jobs that need to be served by a single server which can serve only one job at a time. Jobs have processing times and incur waiting costs. The jobs share their costs through compensation using monetary transfers. The authors characterize the Shapley value rule for this model using fairness axioms. They define the worth of a coalition as the cost incurred by jobs in the coalition if these are the only jobs served in the queue. They precise that there are many other ways to define the worth of a coalition, like considering the dual of their definition, or by assuming that a coalition of jobs are served after the jobs not in the coalition are served.

Yet, other authors consider explicitly a fixed cost component in their cost sharing. In [39] for instance, Anshelevich et al. study the problem of fair cost allocation in network design. The authors show that sharing equally the design cost of each network edge between users whose connections make use of it lead to near-optimal Nash equilibria. An equal sharing of the design cost seems rational as it is not directly related to a user. In our work, an equal sharing of the fixed energy consumption between the service categories may look rational too as it is consumed irrespective of traffic. However, we consider that an equal sharing does not reflect the impact of traffic on the fixed energy consumption increase, and so, we propose a sharing of the fixed cost based on Shapley value.

## 2.3 Sharing the responsibility of service categories in the fixed energy consumption

Again, based on [10] and measurements carried out on a real operational European network by the network operator, the power consumption of a network equipment can be modeled as a linear function of the load with a variable and a fixed components.

Let  $P_k(t)$  denote the power consumption of a network equipment at instant  $t$ . It is given by:

$$P_k(t) = P_k^f(t) + (P_k^{max}(t) - P_k^f(t)) \rho_k(t) \quad (2.1)$$

where  $P_k^f(t)$  is the fixed power component,  $P_k^{max}(t)$  the maximum power consumption,  $\rho_k(t)$  the load and  $(P_k^{max}(t) - P_k^f(t)) \rho_k(t)$  the variable power component.

Let  $E_k$  denote the energy consumption of the network equipment  $k$  over the time period  $\Delta T$ . It is given by:

$$\begin{aligned} E_k &= \int_{\Delta T} P_k(t) dt \\ &= \int_{\Delta T} (P_k^f(t) + (P_k^{max}(t) - P_k^f(t)) \rho_k(t)) dt \end{aligned}$$

Let  $E$  denotes the energy consumption of a network composed of  $K$  equipment, then  $E = \sum_{k=1}^K E_k$ .

Let  $E^v$  and  $E^f$  denote the variable and fixed energy components of the network respectively:

$$E^v = \sum_{k=1}^K \int_{\Delta T} (P_k^{max}(t) - P_k^f(t)) \rho_k(t) dt \quad (2.2)$$

$$E^f = \sum_{k=1}^K \int_{\Delta T} P_k^f(t) dt \quad (2.3)$$

Let us first consider a radio access network with only one radio technology (homogeneous network) transporting a set  $\mathcal{N}$  of  $N$  service categories, consuming energy  $E$  which is to be assigned to the service categories. We have,

$$E = E^v + E^f \quad (2.4)$$

Let  $E_i$  denote the energy consumption assigned to service category  $i$ , with variable and fixed components  $E_i^v$  and  $E_i^f$ , respectively,

$$E_i = E_i^v + E_i^f \quad (2.5)$$

The share of service category  $i$  in the variable energy consumption is its traffic proportion  $\varphi_i$  as it is load-dependent. That is,

$$E_i^v = \varphi_i \times E^v \quad (2.6)$$

As of the fixed energy component, it may seem rational to share it equally between the service categories as it is consumed irrespective of traffic. This is actually the outcome when applying the Shapley value to the total energy consumption of the network (the fixed component is equally assigned to the service categories and the variable component is assigned proportionally to their traffic). However, this energy component increases with traffic over time due to network upgrade operations as depicted in Fig. 1.9, and so, it is somehow related to the services. We propose then to assign to each service category a share of the fixed energy consumption based on its impact on this increase. To do so, we use the Shapley value for its fairness property as axiomatically defined by L. Shapley and presented in the next section. That is,

$$E_i^f = \phi_i \times E^f \quad (2.7)$$

where  $\phi_i$  is the Shapley value of service category  $i$ .

## 2.4 Shapley value

In game theory, a cooperative game (or coalitional game) is a game which allows grouping of players within so-called coalitions, thanks for instance to the possibility of external enforcement of cooperative behavior (e.g., through contract law) [40, 41, 42]. These are opposed to non-cooperative games in which there is no possibility to forge alliances. The payoff of a player in a cooperative game represents its gain or loss in the game. An allocation represents a vector of payoffs. Cooperative games are typically analyzed in the framework of cooperative game theory, which focuses on predicting which coalitions will form, the



joint actions that groups take and the resulting collective payoffs. It is opposed to non-cooperative game theory which focuses on predicting individual players' actions and payoffs and analyzing Nash equilibria.

In cooperative game theory, a solution is a vector of  $\mathcal{R}^N$  that represents an allocation to the players, with  $\mathcal{N}$  the set of players, and  $N$  the number of players. There are two types of solution concepts in cooperative games: the unobjectionable solutions and the equitable solutions. The former guarantee a sharing between the players such that any coalition (grouping of players) cannot increase its gain by leaving the coalition composed of all the players, called the grand coalition. An imputation is a solution that exactly splits the total value of the grand coalition among the players, such that no player receives less than what he could get on his own. The core is the set of imputations under which no coalition has a value greater than the sum of its members' payoffs. Unobjectionable solutions include the core. Therefore, no coalition has an incentive to leave the grand coalition and receive a larger payoff. Equitable solutions take into account some consideration of equity between players. Such solutions include the Shapley value.

The characteristic function  $V$  in a cooperative game is a function which associates to each coalition a number corresponding to its value. A cooperative game is with transferable utility when the players can share their common value among them in any way. A cooperative game with transferable utility is represented by the number of players in the game and the characteristic function. Let  $L(N)$  denote the set of subsets of  $\mathcal{N}$ . A characteristic function is an element of  $\mathcal{R}^{L(N)}$ .

L. Shapley approaches the Shapley value axiomatically. That is, he asked what kind of properties we might expect such a solution concept to satisfy, and he characterized the mapping  $\phi$  that satisfies these properties.

Shapley's first axiom asserts that only the role of a player in the game should matter, not his specific name or label in the set  $\mathcal{N}$ .

**Axiom 1 (Symmetry).** *For any  $V$  in  $\mathcal{R}^{L(N)}$ , any permutation  $\pi : \mathcal{N} \rightarrow \mathcal{N}$ , and any player  $i$  in  $\mathcal{N}$ ,  $\phi_{\pi(i)}(\pi V) = \phi_i(V)$*

A permutation of the set of players  $\mathcal{N}$  is any function  $\pi : \mathcal{N} \rightarrow \mathcal{N}$  such that, for every  $j$  in  $\mathcal{N}$ , there exists exactly one  $i$  in  $\mathcal{N}$  such that  $\pi(i) = j$ . Given any such permutation  $\pi$  and any coalitional game  $V$ , we let  $\pi V$  be the coalitional game such that

$$\pi V(\{\pi(i) | i \in S\}) = V(S), \quad \forall S \subseteq \mathcal{N}$$

That is, the role of any player  $i$  in  $V$  is essentially the same as the role of the player  $\pi(i)$  in  $\pi V$ .

Shapley's second axiom asserts that the players in a carrier set should divide their joint worth (which is equal to the worth of the grand coalition) among themselves, and allocate nothing to the dummies.

**Axiom 2 (Carrier).** *For any  $V$  in  $\mathcal{R}^{L(N)}$  and any coalition  $R$ , if  $R$  is a carrier of  $V$ , then  $\sum_{i \in R} \phi_i(V) = V(R)$ .*

We say that a coalition  $R$  is a carrier of a coalitional game  $V$  iff

$$V(S \cap R) = V(S), \quad \forall S \subseteq N \tag{2.8}$$

If  $R$  is a carrier of  $V$ , then all the players who are not in  $R$  are called *dummies* in  $V$ , because their entry into any coalition cannot change its worth.

**Axiom 3** (Linearity). For any two coalitional games  $V$  and  $W$  in  $\mathcal{R}^{L(N)}$ , any number such that  $0 \leq p \leq 1$ , and any player  $i$  in  $N$ ,

$$\phi_i(pV + (1-p)W) = p\phi_i(V) + (1-p)\phi_i(W) \quad (2.9)$$

Shapley showed that there is a unique mapping  $\phi$  called the *Shapley value* that satisfies these three axioms.

**Theorem 1.** *There is exactly one function  $\phi : \mathcal{R}^{L(N)} \rightarrow \mathcal{R}^N$  that satisfies the three axioms of the Shapley value. This function satisfies the following equation, for every  $i$  in  $N$  and every  $V$  in  $\mathcal{R}^{L(N)}$ :*

$$\phi_i(V) = \sum_{S \subseteq N-i} \frac{|S|!(|N|-|S|-1)!}{|N|!} (V(S \cup \{i\}) - V(S)) \quad (2.10)$$

$V$  is superadditive if for any coalitions  $S$  and  $T$  in  $L(N)$  such that  $S \cap T = \emptyset$ , we have

$$V(S \cup T) \geq V(S) + V(T)$$

If  $V$  is superadditive, then the Shapley value must be individually rational, in the sense that

$$\phi_i(V) \geq V(\{i\}), \forall i \in N$$

The formula for the Shapley value can be equivalently written

$$\phi_i(V) = \sum_{S \subseteq N-i} \frac{|S|!(|N|-|S|-1)!}{|N|!} (V(N \setminus S) - V(S)) \quad (2.11)$$

## 2.5 Sharing scenarios

### 2.5.1 Case with no mandatory players

Shares of the service categories and values of the coalitions are normalized by the fixed energy consumption, unless otherwise stated.

Let  $S$  denote a set of service categories, which we denote a "coalition", and  $s$  its size, i.e., the number of service categories in the coalition.

We assume that the value of coalition  $S$  is the ratio of its traffic volume to the traffic volume of coalitions having the same size as  $S$ . That is,

$$V(S) = \frac{\sum_{k_1=1}^s v_{k_1,S}}{\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1,S_{j_2}}} \quad (2.12)$$

where  $\binom{N}{s}$  is the number of coalitions of size  $s$  and  $v_{k,S}$  is the traffic volume of the  $k^{\text{th}}$  element of a coalition.  $k_1$  spans over the service categories inside a coalition,  $j_2$  spans over coalitions of size  $s$  and  $(\cdot)$  is the binomial coefficient.

The intuition behind the characteristic function can be seen as follows. Over the long term, traffic of different service categories increases, and so does the energy consumption. Our focus is on the fixed component of this energy consumption. We assume that the impact of a service category in the fixed energy consumption increase is equal to its traffic proportion. And so, we share the fixed component of the energy consumption between the service categories proportionally to their traffic, taking these service categories within coalitions. On

the short term, the fixed energy component is constant, and so, at this scale, what matters is the number of players per coalition, and not the traffic volume of each player. And so, the proportional sharing done at the longer scale is done only on coalitions of the same size.

This characteristic function is a particular choice motivated by the above rationale. Other choices for other characteristic functions are possible.

This characteristic function can be expressed as follows:

$$V(S) = \frac{\varphi(S)}{\binom{N-1}{s-1}}$$

where  $\varphi(S)$  is the traffic proportion of coalition  $S$ .

The derivation of this expression can be found in Appendix A.

Based on Eqn. (2.10), the share  $\phi_i$  of player  $i$  can be equivalently written as Eqn. (2.13) [43],

$$\phi_i(V, S) = \frac{1}{N!} \sum_{s=1}^N (N-s)!(s-1)! \sum_{j_1=1}^{\binom{N-1}{s-1}} \delta(\{i\}, S) \quad (2.13)$$

where  $\delta(\{i\}, S) = V(S_{j_1, \{i\}}) - V(S_{j_1, \{i\}} \setminus \{i\})$  is the marginal contribution of player  $i$  in coalition  $S$ . It represents the cost gained or lost by coalition  $S$  because of player  $i$ .

The computational complexity of (2.13) grows exponentially in the number of service categories, which could represent an obstacle for implementation. So, we propose a closed-form expression which lower the computational complexity, derived from (2.13).

The closed-form expression of the Shapley value of player  $i$  is given by:

$$\phi_i(N, \varphi_i) = \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) \varphi_i + \left( \sum_{s=2}^N \frac{(\binom{N-1}{s-2} - \binom{N-1}{s-1}) \binom{N-2}{s-2}}{\binom{N-1}{s-1} \binom{N-1}{s-2} s \binom{N}{s}} \right) (1 - \varphi_i) \quad (2.14)$$

The derivation of this expression can be found in Appendix A.

## 2.5.2 Case with a mandatory player

Let us now consider a scenario with a mandatory player. This is the case for instance when an operator has the obligation, by the state, to offer a given service, notably Voice, when deploying a network infrastructure. Therefore, we suppose that the network cannot provide a set of service categories not containing the mandatory service category. That is:

$$\begin{cases} V(S) = \frac{\varphi(S)}{\binom{N-1}{s-1}} & \text{if } i^* \in S \\ V(S) = 0 & \text{if } i^* \notin S \end{cases} \quad (2.15)$$

where  $i^*$  denote the mandatory player.

Shares  $\phi_{i^*}$  and  $\phi_o$  of the mandatory player  $i^*$  and a non mandatory player  $o$ , respectively, are obtained from (2.13).

The closed-form expression of the Shapley value of the mandatory player is given by:

$$\phi_{i^*}(N, \varphi_{i^*}) = \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) \varphi_{i^*} + \left( \sum_{s=2}^N \frac{\binom{N-2}{s-2}}{\binom{N-1}{s-1} s \binom{N}{s}} \right) (1 - \varphi_{i^*}) \quad (2.16)$$

The derivation of this expression can be found in Appendix B.1.

The closed-form expression of the Shapley value of a non mandatory player is given by:

$$\begin{aligned} \phi_o(N, \varphi_{i^*}, \varphi_o) = & \left( \sum_{s=2}^N \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-2}{s-2}}{\binom{N-1}{s-1} \binom{N-1}{s-2} s \binom{N}{s}} \right) \varphi_{i^*} + \left( \sum_{s=2}^N \frac{\binom{N-2}{s-2}}{\binom{N-1}{s-1} s \binom{N}{s}} \right) \varphi_o \\ & + \left( \sum_{s=3}^N \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-3}{s-3}}{\binom{N-1}{s-1} \binom{N-1}{s-2} s \binom{N}{s}} \right) (1 - \varphi_{i^*} - \varphi_o) \end{aligned} \quad (2.17)$$

The derivation of this expression can be found in Appendix B.2.

### 2.5.3 Case with only mandatory players

Let us consider a scenario where all the players are mandatory. The closed-form Shapley value of player  $i$  is given by:

$$\phi_i(N) = \frac{1}{N} \quad (2.18)$$

The derivation of this expression can be found in Appendix C.

Thus, when all the players are mandatory, the fixed energy component is equally assigned to the service categories. A uniform sharing is then a special case of the Shapley-based model.

### 2.5.4 Heterogeneous radio access network

When the network is composed of several radio access technologies, we share the responsibility of the service categories per technology.

Let  $\mathcal{T}$  denote the set of radio technologies,  $\mathcal{F}_t$  the set of service categories provided by the sub-network implementing the radio technology  $t$ ,  $E_t^v$  ( $E_t^f$ ) the variable (fixed) energy consumption of sub-network  $t$  and  $\varphi_{i,t}$  the traffic proportion of service category  $i$  regarding the sub-network  $t$ . The total network energy consumption (variable and fixed) assigned to service category  $i$  is given by:

$$E_i = \sum_{t \in \mathcal{T}} \varphi_{i,t} E_t^v + \phi_{i,t} E_t^f \quad (2.19)$$

If  $\theta_t$  is the share of the variable component, then,

$$E_i = \sum_{t \in \mathcal{T}} (\theta_t \varphi_{i,t} + (1 - \theta_t) \phi_{i,t}) E_t \quad (2.20)$$

where  $E_t$  is the energy consumption of sub-network  $t$ .

### 2.5.5 Evolving network infrastructure

Over long periods of time, typically on the order of years, the network infrastructure needs to be upgraded in order to keep up with load increase, as depicted in Fig. 1.9.

When there are several upgrade levels, the share of a service category in the fixed energy component of the network is derived from its shares per technology and per upgrade level. Let  $\mathcal{L}$  denote the set of upgrade levels,  $\varphi_{i,t,l}$  the traffic proportion of service category  $i$  on sub-network  $t$  considering upgrade level  $l$  and  $E_{t,l}^v$  ( $E_{t,l}^f$ ) the variable (fixed) energy consumed by sub-network  $t$  regarding upgrade level  $l$ .

$$E_i = \sum_{l \in \mathcal{L}} \sum_{t \in \mathcal{T}} (\varphi_{i,t,l} E_{t,l}^v + \phi_{i,t,l} E_{t,l}^f) \quad (2.21)$$

Traffic variations strongly impact network upgrade, and so, one needs to make a sharing of energy and equipment costs which takes into account this aspect. For this purpose, one can consider the variations of traffic,  $\delta v$ , instead of the traffic volumes,  $v$ , in the model. Traffic variation  $\delta v$  of a service category represents its traffic increase between two upgrade levels. At the first upgrade level, traffic variations correspond to traffic volumes.

$$E_i = \sum_{l \in \mathcal{L}} \sum_{t \in \mathcal{T}} \left( \frac{\delta v_{i,t,l}}{\sum_{k \in \mathcal{F}_t} \delta v_{k,t,l}} E_{t,l}^v + \phi_{i,t,l} E_{t,l}^f \right) \quad (2.22)$$

## 2.6 Implementation issues

Fig. 2.1 shows the runtime (in seconds) of two algorithms for the computation of the Shapley values of the service categories, one using the Shapley value function (2.13) - denoted by Classical - and the other using the closed-form expression of the Shapley value (2.14) - denoted by Optimized.

The algorithm using the closed-form expression (2.14) has a runtime almost independent of the number of service categories in the network (less than 1 second for up to 50 service categories, the maximum number of service categories we measure in the considered network), while the algorithm using (2.13) has a computational complexity growing exponentially in the number of service categories, does not converge and has some resource limitation starting from a certain number of service categories (depending on the simulation environment). This is because the Shapley value function computes the marginal contributions of each service category in  $2^N - 1$  coalitions, unlike the closed-form expressions we derive from it. These expressions are linear in traffic proportion and can be written in the following general forms:

$$\phi_i(N, \varphi_i) = A(N)\varphi_i + B(N) \quad (2.23)$$

for (2.14),

$$\phi_{i^*}(N, \varphi_{i^*}) = C(N)\varphi_{i^*} + D(N) \quad (2.24)$$

for (2.16) and

$$\phi_o(N, \varphi_{i^*}, \varphi_o) = E(N)\varphi_{i^*} + F(N)\varphi_o + G(N) \quad (2.25)$$



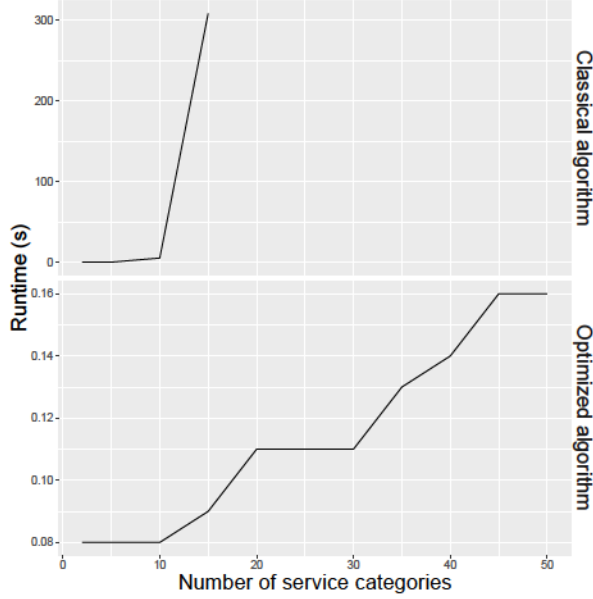


Figure 2.1: Runtimes of the classical-based and closed-form-based Shapley value algorithms.

for (2.17), where  $A(N)$  is the impact of player  $i$  traffic in its share,  $C(N)$  the impact of the mandatory player  $i^*$  traffic in its share,  $E(N)$  the impact of the mandatory player  $i^*$  traffic in an optional player  $o$  share, and  $F(N)$  the impact of an optional player  $o$  in its share.  $B(N)$  is the lower bound on player  $i$  share,  $D(N)$  the lower bound on the mandatory player  $i^*$  share and  $G(N)$  the lower bound on an optional player  $o$  share.

For example, for  $N = 5$ ,  $\phi_i(\varphi_i) = A(5)\varphi_i + B(5) = 0.417 \varphi_i + 0.117$ . As depicted in Figs. 2.2 and 2.3,  $A(N), B(N), C(N), D(N), G(N)$  are asymptotically equivalent to  $1/N$ .  $E(N)$  and  $F(N)$  tend faster to 0. That is (2.14), (2.16) and (2.17) become respectively  $\phi_i(N, \varphi_i) = \frac{1+\varphi_i}{N}$ ,  $\phi_{i^*}(N, \varphi_{i^*}) = \frac{1+\varphi_{i^*}}{N}$  and  $\phi_o(N) = \frac{1}{N}$  for a large number of service categories.

It is worth to note that  $\phi_i(\varphi_i) = A(2)\varphi_i + B(2) = \varphi_i$  for  $N = 2$ , which means that the Shapley-based model is equivalent to a proportional sharing when considering just 2 service categories and if none is considered as a mandatory service.

In addition, besides the reduction of the computational complexity, the closed-form expressions give the lower bound on the players shares in the fixed energy consumption. Considering for instance the scenario without a mandatory player, and 5 service categories, the lower bound on the players shares is  $B(5) = 12\%$ .

As illustrated in Fig. 2.3, the lower bound on the players shares is a function of the number of service categories defined in the model. Considering again the scenario without a mandatory player, the lower bound on the players shares is the highest when considering 5 service categories (12%) and the lowest when considering 2 service categories (0%).

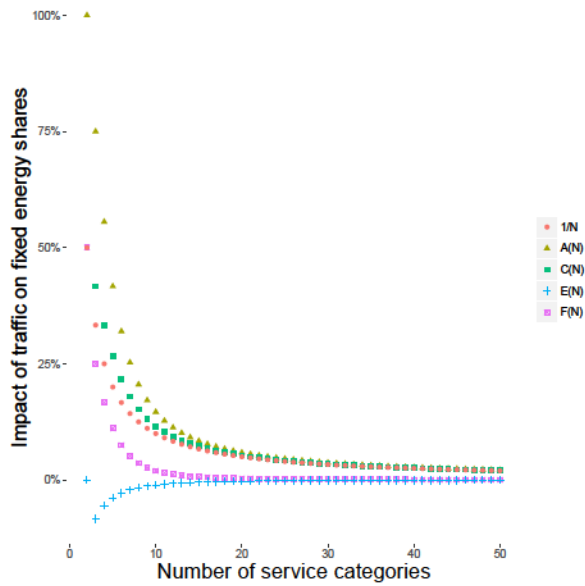


Figure 2.2: Impact of traffic proportions on shares in fixed energy consumption.

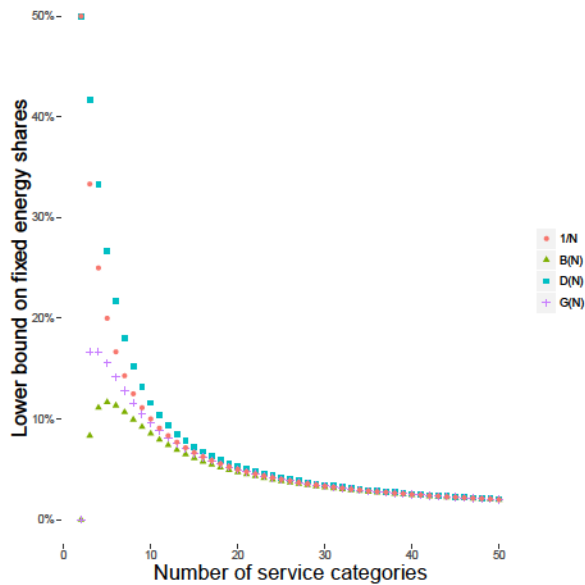


Figure 2.3: Lower bound on shares in fixed energy consumption.

## 2.7 Numerical applications

We consider a real operational European radio access network. The period of the study covers two years representing a mature 2G/3G network with early LTE deployment and associated traffic increase. We measure all voice and data

services that are transmitted in the network with the following segmentation for the service categories: two large ones, namely streaming and web browsing, and three smaller ones: download, voice and other data services. Fig. 2.4 shows their traffic proportions as taken from the real data set. We consider traffic and energy consumption of the 3G sub-network.

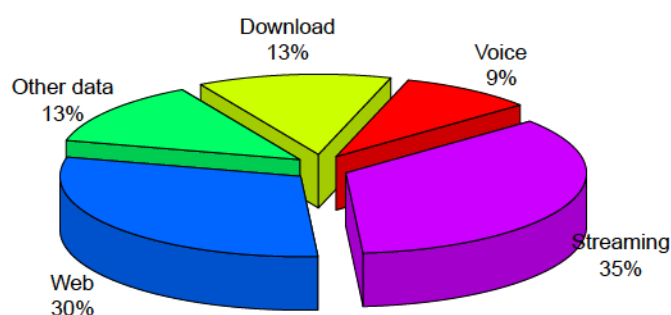


Figure 2.4: Traffic proportions per service category.

The share of a service category in the variable energy consumption equals its traffic proportion as this energy component is load-dependent. This implies that data services are responsible for about 90% of the UMTS Terrestrial Radio Access Network (UTRAN) variable energy consumption. These services are dominated by Over The Top (OTT) actors like Google.

We next turn to the sharing of the responsibility of the service categories in the fixed energy consumption.

### 2.7.1 Case with no mandatory player

We show in Fig. 2.5 the sharing achieved with our Shapley-based proposal alongside with two other approaches: uniform and proportional sharing. Again, a uniform sharing consists in assigning the fixed energy consumption equally to the service categories, and a proportional sharing consists in assigning to each service category a share equal to its traffic proportion.

A uniform sharing favors service categories having a large traffic volume as compared to a proportional sharing, and it is the reverse for service categories





Figure 2.5: Shares in fixed energy consumption: uniform, proportional and Shapley-based sharing.

having a small traffic volume. Our Shapley-based model achieves a trade-off given that service categories having a large traffic volume, namely streaming and web, are assigned a lower share than with a proportional approach, and those having a small traffic volume, namely voice, download and other data services are assigned a lower share with regard to a uniform sharing.

This is an appreciable outcome for streaming and web as it does not penalize them a lot and acknowledges the fact that they are major drivers for network activity, and so it is for service categories having a small traffic volume as it does not make them too much responsible for the fixed energy consumption and encourages their transport as well as the introduction of new ones.

Based on our Shapley-based model, data services are responsible for 85% of the UTRAN fixed energy component.

### 2.7.2 Case with a mandatory player

We now turn to the case when Voice is mandatory due to legal constraints.

As depicted in Fig. 2.6, the mandatory nature of Voice is reflected in our Shapley-based model which increases significantly its share from 15% to 29%. It is an expected outcome because the operator would be mandated by the law to implement and offer it on a national basis. Indeed, to offer this service, the operator would need to deploy a network and dimension it in such a way to reach all the citizens of the given country. In this case, the network can be seen as initially deployed to transport primarily Voice, and so it is natural that it would take a large part of the share in the energy consumption (yet not all of it since it is sharing the infrastructure with "subsequent" service categories).

The aim of the regulator is not necessarily to increase the share of Voice in the energy consumption of the network, but notably to guarantee some basic services on a national basis.

Here too, the Shapley-based model is a trade-off. A trade-off is not required for Voice as a mandatory player because it is obliged to be delivered whatever the sharing model.

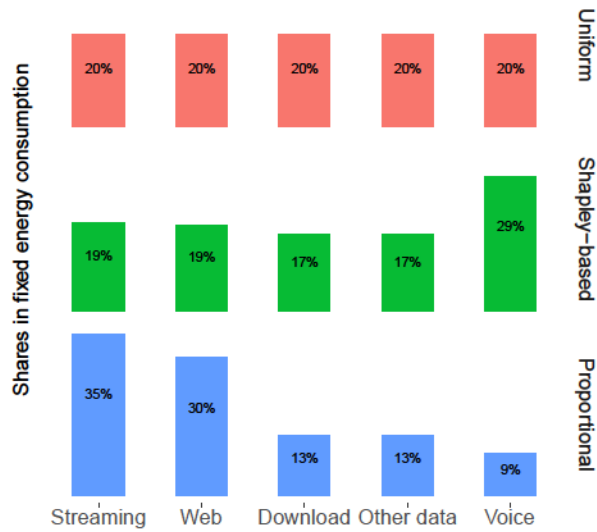


Figure 2.6: Shares in fixed energy consumption - Voice is a mandatory player.

### 2.7.3 Case of an evolving network infrastructure

We now study the case when the network infrastructure is upgraded in order to keep up with traffic increase. Fig. 2.7 depicts the traffic proportions of the same service categories over two periods of time corresponding to two network upgrade levels, termed levels 1 and 2 in the figure. We consider traffic prediction in this scenario.

Here too, each service category is assigned a share in the variable energy consumption equal to its traffic proportion, and so, the corresponding figure is omitted. As of the fixed energy consumption, Fig. 2.8 shows the new shares based on our Shapley-based model (2.14), at each upgrade level, considering the traffic volumes and the traffic variations at level 2.

Considering the traffic volumes puts the weight on service categories having a large traffic volume. Considering the traffic variations puts the weight on service categories whose traffic increases rapidly, reflecting their actual role in the necessity of upgrading the network infrastructure (adding new equipment in the network), which in turn increases the network energy consumption.

It is important to note that traffic increase and traffic volumes are correlated in the studied network, i.e., service categories having large traffic volumes tend

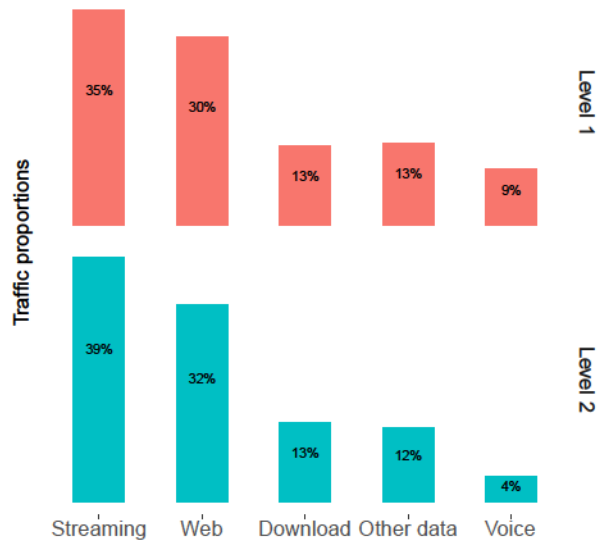


Figure 2.7: Traffic per service category - case of evolving network infrastructure.

to increase faster in terms of traffic. As a result, we note a similar sharing (in terms of weights) of the responsibility of the service categories in the fixed energy consumption whether we consider traffic volumes or traffic increases.

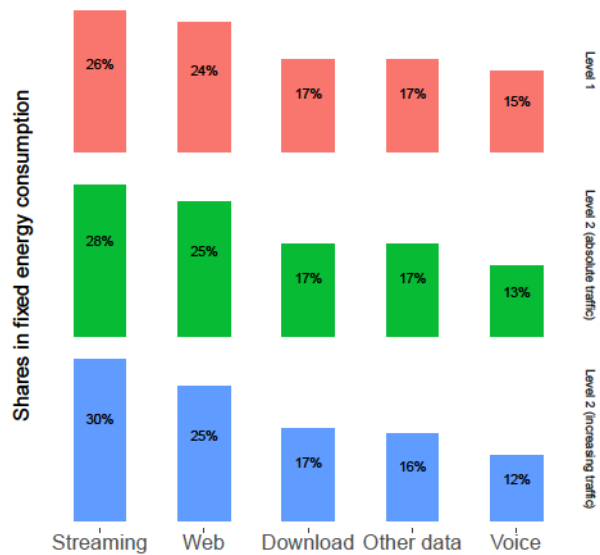


Figure 2.8: Shares in fixed energy consumption - case of evolving network infrastructure.

## 2.8 Conclusion

We investigated in this chapter how to share the responsibility of service categories in the fixed energy consumption of a radio access network. It may seem rational to equally assign the fixed energy consumption to service categories as it is consumed irrespective of traffic. However, it increases with traffic over time due to network upgrade operations and is then somehow related to services. Because of this, we assigned to each service category a share of the fixed energy consumption based on its impact on this increase. We used the Shapley value to do so. Our Shapley-based model puts less weight on service categories having a small amount of traffic than an equal sharing, and less weight on service categories having a large amount of traffic than a sharing proportional to traffic. This is an appreciable outcome as it encourages transport and introduction of small services, and acknowledges the role of larger services as major drivers for network activity.

As the Shapley value has a huge computational complexity, we provided closed-form expressions allowing to compute the shares of the service categories with significant less complexity.

We considered two settings: one with a constant network infrastructure and one with an evolving network infrastructure over longer periods of time. Moreover, we considered the case when some service categories are legally obliged to be provided, such as Voice in several deployed operator networks. The share of a mandatory service category increases significantly as compared to the case when it is not considered to be mandatory.

## Chapter 3

# Sharing the Responsibility of Service Categories in the Fixed Energy Consumption of a End-to-End Network

### 3.1 Context and problem statement

This chapter is a generalization of chapter 2 whose motivation consists in sharing the responsibility of service categories in the fixed energy consumption of a radio access network. In this chapter, we consider the whole network infrastructure.

We decompose the network into 7 blocks, namely, the radio access, the fixed access, the aggregation, the mobile core, the registers, the IP core and the service platforms. We consider 5 service categories: Streaming, Web, Download, other data and Voice. According to ETSI [30], the useful output of an equipment is defined to be its maximum capacity, and is expressed as the number of Erlangs, packets/s, subscribers, or simultaneously attached users. Each service category is assigned a share in the fixed energy consumption of a block with our Shapley-based model introduced in [44]. We first apply it to traffic, then to so-called useful outputs.

Applying our Shapley-based model to useful outputs instead of traffic impacts the shares of the service categories regarding the mobile core only. In fact, the mobile core is composed of equipment whose useful output is not necessarily traffic throughput. For example, the useful output of the serving GPRS support node (SGSN) is the number of simultaneously attached users and not traffic throughput [30].

The remainder of this chapter is organized as follows. In section 3.2, we introduce our model for sharing the responsibility of service categories in the fixed energy consumption of a end-to-end network. Section 3.3 shows some numerical applications of our model run on a real data set taken from an operational European network. Section 3.4 eventually concludes the chapter.

## 3.2 Sharing model

A typical network is composed of a number of blocks, as illustrated in Fig. 3.1. A block is a set of elements with a common general function from an architectural point of view. For example, for radio access networks, we can define two main blocks: the block of base stations and the block of controllers, when applicable. End-users should also be considered as one or more blocks. The partition of one block into sub-blocks should be possible following the need and the coherence of the model. Each block or sub-block is composed of a list of elements. An element may be a network equipment, a server or a device that is used to deliver the service to the end-user. One base station is for example an element.

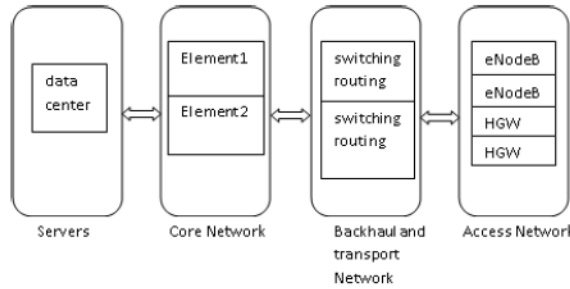


Figure 3.1: Example of a mobile network decomposition per block.

### 3.2.1 Components of a block energy consumption

As stated earlier, the energy consumption of a network equipment is composed of 2 components: a variable and a fixed one. Let  $E_k^f$  denote the fixed energy component of equipment  $k$  over time period  $\Delta T$ , and  $E_k^v$  its variable energy component.

The overall energy consumption of a block is the sum of individual energy consumptions of its elements. Let  $K$  denote the number of elements in block  $j$ , and  $E_j$  the energy consumption of block  $j$ . We have:

$$E_j = \sum_{k=1}^K E_k^f + E_k^v \quad (3.1)$$

Hence, the variable energy component of block  $j$  is given by  $E_j^v = \sum_{k=1}^K E_k^v$  and its fixed component is given by  $E_j^f = \sum_{k=1}^K E_k^f$ .

### 3.2.2 Sharing the responsibility of service categories in a block fixed energy consumption

Let  $i$  denote a service category,  $E_{i,j}^f$  the fixed energy assigned to service category  $i$  regarding block  $j$  and  $E_{i,j}^v$  the variable energy assigned to service category  $i$  regarding block  $j$ . Let  $\varphi_{i,j}$  denote the traffic proportion of service category  $i$  with respect to block  $j$ .



A service category is assigned a share in the variable energy consumption equal to its traffic proportion since this energy component is load-dependent. So,

$$E_{i,j}^v = \varphi_{i,j} \times E_j^v \quad (3.2)$$

Each service category is assigned a share in the fixed energy consumption with our Shapley-based model introduced in the preceding chapter. So, the share of service category  $i$  in the fixed energy consumption of block  $j$  is given by:

$$E_{i,j}^f = (A(N)\varphi_{i,j} + B(N)) \times E_j^f \quad (3.3)$$

where

$$A(N) = \frac{1}{N} + \sum_{s=2}^N \frac{1}{s \binom{N}{s}} - \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-2}{s-2}}{(\binom{N-1}{s-1}) (\binom{N-1}{s-2}) s \binom{N}{s}} \quad (3.4)$$

$$B(N) = \sum_{s=2}^N \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-2}{s-2}}{(\binom{N-1}{s-1}) (\binom{N-1}{s-2}) s \binom{N}{s}} \quad (3.5)$$

where  $N$  is the number of service categories and  $(\cdot)$  is the binomial coefficient.

### 3.3 Numerical applications

In this section, we consider the architecture of a real European network as illustrated in Fig. 3.2.

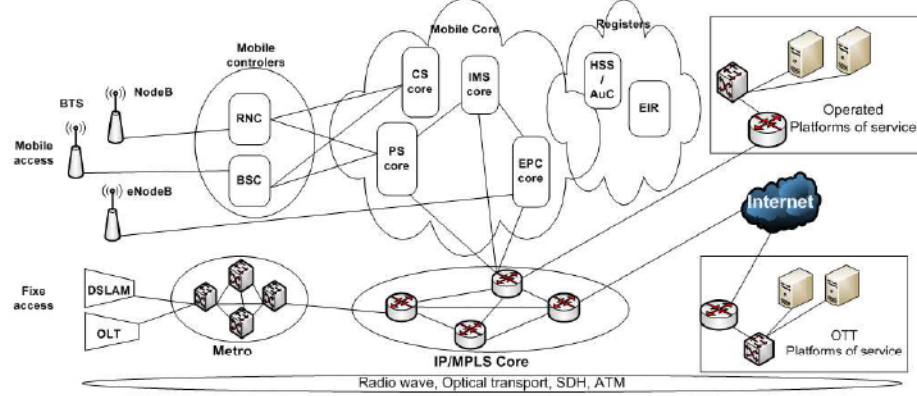


Figure 3.2: End-to-end architecture of a telecommunication network.

The studied network consists of a fixed access, a mobile access, an aggregation, a mobile core, the registers, an IP core and a streaming server. We, again, consider 5 service categories, namely, Streaming, Web, Download, other data services and Voice.

#### 3.3.1 Shapley value applied to traffic

The number of service categories  $N$  to be considered in the sharing depends on the equipment under consideration. For example, mobile switching centers (MSCs) do not deliver data services, and SGSNs do not deliver Voice. In this

Table 3.1: Sharing model parameters

Parameters	Values
A(1)	1
B(1)	0
A(4)	0.556
B(4)	0.111
A(5)	0.417
B(5)	0.117

Table 3.2: Weight coefficients

Network block	Weight
CS core energy consumption	$0.21 \times$ Mobile core energy consumption
PS core energy consumption	$0.21 \times$ Mobile core energy consumption
EPC core energy consumption	$0.48 \times$ Mobile core energy consumption
IMS core energy consumption	$0.10 \times$ Mobile core energy consumption
SGSN network energy consumption	$0.16 \times$ PS core energy consumption
HSS network energy consumption	$0.92 \times$ Registers energy consumption

work, Voice refers to circuit switched voice. Based on the possible values of  $N$  in our study, the values of parameters  $A(N)$  of Eqn. (3.4) and  $B(N)$  of Eqn. (3.5) can be found in Tab. 3.1.

The mobile core is composed of different sub-blocks, namely, the circuit switched core (CS core), packet switched core (PS core), evolved packet core (EPC) and IP multimedia subsystem core (IMS core). These sub-blocks have their own traffic proportions, and so, the service categories are assigned different shares. In order to compute the shares of the service categories regarding the mobile core, we need to know the weights of the sub-blocks in the mobile core energy consumption. Values of these weights are depicted in Tab. 3.2. They come from measurements carried out on the studied network and can be found in Appendix D (we consider energy consumption values of year 2016, knowing that the IMS energy consumption was 619 MWh the same year).

Given a block, the share of a service category is the weighted sum of its shares in the fixed and variable energy components of the block. Its share in the variable energy component is weighted with the proportion of variable energy in the total energy consumption of the block. We consider the variable energy component to account for 20% of a block energy consumption [11, 45].

Fig. 3.3 depicts the shares of the service categories in the energy consumption of the studied operational European network per block. We observe the following:

- Energy consumption of the streaming server is allocated in total to the streaming service.
- The fixed access and aggregation have the same energy sharing figures



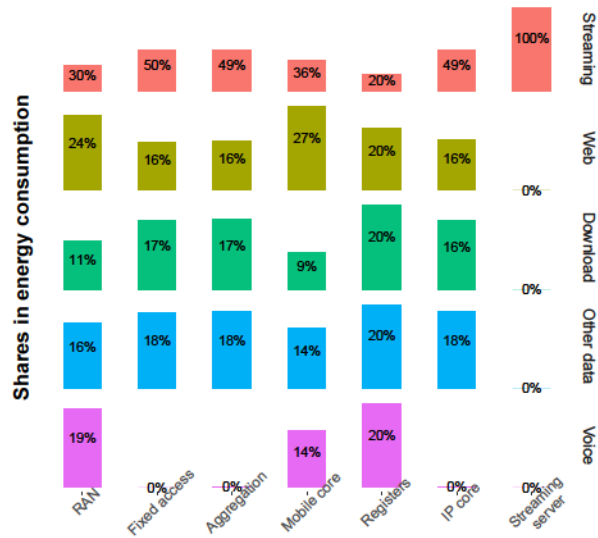


Figure 3.3: Shares in end-to-end network energy consumption.

since we do not consider mobile controllers, i.e., BSCs and RNCs, in the scope of this investigation. So, the aggregation network is composed of Ethernet switches transporting the traffic originating from the fixed access. As a result, these blocks have the same traffic distribution, and so, the same shares for the service categories.

- Streaming is the service that consumes the most, whatever the block under consideration, except for the registers given that their traffic consists essentially of requests that are supposed to be evenly distributed among the service categories. Streaming consumes nearly half the energy of the fixed access, aggregation and IP core. In fact, Streaming represents the vast majority of traffic in the network, around 60% of the fixed access, aggregation and IP core traffic regarding the studied network.
- Shares regarding the mobile core are different from those of the mobile access (RAN), although these blocks deal with the same traffic. Indeed, traffic originating from the mobile access is not operated by the same equipment in the mobile core depending on the nature of the service. Because of this, the mobile core has different shares per sub-block, resulting in global shares different from those of the mobile access.
- Shares regarding the IP core are quite similar to those of the fixed access, even though the IP core deals with traffic originating both from the fixed and mobile accesses. Indeed, this outcome is because the fixed traffic accounts for a huge amount of IP traffic. For example, the fixed traffic (including WiFi traffic) accounts for around 80% of overall IP traffic on the network under investigation.

### 3.3.2 Shapley value applied to useful outputs

In the above analysis, we assigned a share of the blocks energy consumption to each service category based on traffic. In this section, we consider the so-called useful outputs to assign to each service category a share in the end-to-end network energy consumption. Again, the useful output of an equipment is defined to be its maximum capacity and is expressed as the number of Erlangs, packets/s, subscribers, or simultaneously attached users according to ETSI [30]. It might be more rational to consider useful output instead of traffic for some equipment. For example, it makes more sense to discuss the energy consumption of the home subscriber server (HSS) in terms of number of subscribers instead of traffic throughput, because this equipment is designed for registering subscribers.

#### Simulation setup

The useful outputs of network equipment under investigation are given in Tab. 3.3. The first column shows the network equipment we consider in the scope of this investigation, column 2 gives the corresponding useful output, based on ETSI [30]. In column 3, we give the number of service categories operated by the given equipment. The last column shows the useful output proportions of the service categories.

Traffic proportions of the mobile and fixed accesses come from measurements carried out on the network under investigation by the network operator.

MSCs deal with circuit switched services, and so, we suppose that only Voice impacts these equipment.

We assume that every end-user uses all the data services, and so, data service categories have the same impact on SGSNs in terms of simultaneously attached users. Voice does not impact SGSNs given that these equipment provide data services only. The same reasoning applies for gateway GPRS support nodes (GGSNs), mobility management entities (MMEs), packet gateways (PGWs) and signaling gateways (SGWs).

We also assume that data services have the same mean packet size, and so, proportions which should be computed based on throughput expressed in packet per second can be approximated with traffic proportions, which are more easily measurable. In the case of GGSNs, we consider 3G data traffic proportions only. In fact, GGSNs deliver 2G and 3G data traffic, however, the 2G data traffic is negligible compared to the 3G traffic. For example, we measured 1% 2G data traffic versus 34% 3G data traffic on the studied network. When it comes to PGWs and SGWs, we consider 4G traffic proportions instead.

Users registered in the HSS use all the service categories (Voice and data), and so, the service categories have the same impact on this equipment in terms of number of registered subscribers. In fact, 2G subscribers cannot be considered as voice-only users given that they do generate data traffic; For example, there are 4% of 2G subscribers on the studied network, and they generate 1% of total data traffic. We keep the same reasoning with equipment identity registers (EIRs) in terms of number of registered mobile phones.

Ethernet switches carry traffic originating from the fixed access, and so, these two blocks have the same traffic proportions.

Traffic proportions of the IP core are the weighted sum of fixed and mobile

accesses traffic proportions; The fixed traffic accounting for 80% of total traffic, based on measurements carried out on the investigated network by the network operator. We consider WiFi traffic to be part of the fixed access traffic.

As we consider a streaming server, 100% of its traffic is due to Streaming.

### **Useful-output-based sharing of the responsibility of service categories in the mobile core energy consumption**

As stated above, only the shares of the mobile core are impacted when applying our Shapley-based model to useful outputs instead of traffic. In fact, the useful output of the network blocks, except the mobile core and registers, is traffic throughput, and so, the shares of the service categories are not altered compared to the case when we apply the Shapley-based model to traffic. When it comes to the mobile core block, some equipment useful output is not traffic throughput. This is the case for SGSNs, for example, whose useful output is the number of simultaneously attached users.

Although the useful output of registers is not traffic throughput, we still have an equal sharing of the energy consumption given that the number of registered subscribers in the HSS and the number of mobile devices in EIRs are equally distributed over the service categories, like the requests. As a result, only the figure of the mobile core block is modified as shown in Fig. 3.4.

It is important to note that the useful-output-based sharing is beneficial to service categories having a large traffic volume as compared to the traffic-based sharing. Indeed, more equipment have their energy consumption equally assigned to the service categories since their useful output is uniformly distributed. This is the case for the SGSN, the HSS and the EIR for example. Replacing a sharing proportional to traffic proportions with a uniform sharing is naturally beneficial to service categories having a large traffic volume as illustrated in the figure. However, the share of Voice remains unchanged because the energy consumption of the CS core is the same.

### **Hybrid sharing of the responsibility of service categories in the mobile core energy consumption**

Since the variable energy consumption is consumed proportionally to the load [10], the share of a service category in this energy component is equal to its traffic proportion.

As of the fixed energy consumption, we assign it to the service categories based on their utility for the block, expressed by the useful output. For example, the share of a data service category in the variable energy consumption of SGSNs is equal to its traffic proportion, while the fixed energy consumption is equally assigned since the simultaneously attached users on a SGSN are equally distributed over the data service categories.

As a result, we have a hybrid sharing of the mobile core energy consumption in the sense that its variable energy consumption is assigned to the service categories based on their traffic proportions, while its fixed energy consumption is assigned based on useful outputs. The shares of the service categories in the mobile core energy consumption considering a hybrid sharing are shown in Fig. 3.5.

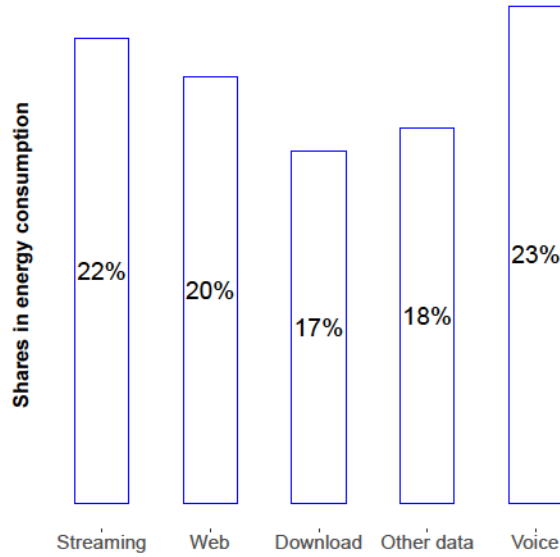


Figure 3.4: Shares in mobile core energy consumption: useful-output-based sharing.

Let us note that the hybrid sharing lies between the traffic-based and useful-output-based sharing, so it is a trade-off between the service categories in the sense that those having a large volume of traffic get a lower share than with a traffic-based sharing, and so it is for service categories having a smaller volume of traffic as compared to a useful-output-based sharing.

### 3.4 Conclusion

In this chapter, we shared the responsibility of service categories in the fixed energy consumption of a end-to-end network. We decomposed the entire network into 7 blocks, namely, the radio access, the fixed access, the aggregation, the mobile core, the registers, the IP core and the service platforms. We applied our Shapley-based model per block. We considered 5 service categories, namely, Streaming, Web, Download, other data and Voice.

Streaming is the service that consumes most whatever the network block. In fact, this service accounts for the vast majority of Internet traffic, around 60% of the fixed access, aggregation and IP core traffic regarding the operational European network under investigation.

The mobile access and mobile core have not the same shares although they deal with the same traffic. Indeed, the mobile core is composed of sub-blocks with different traffic proportions resulting in different global shares as compared to the mobile access.

We also applied our Shapley-based model to useful outputs. Only the shares of the mobile core are modified, considering the studied network. Indeed, the mobile core is composed of equipment whose useful output is not necessarily

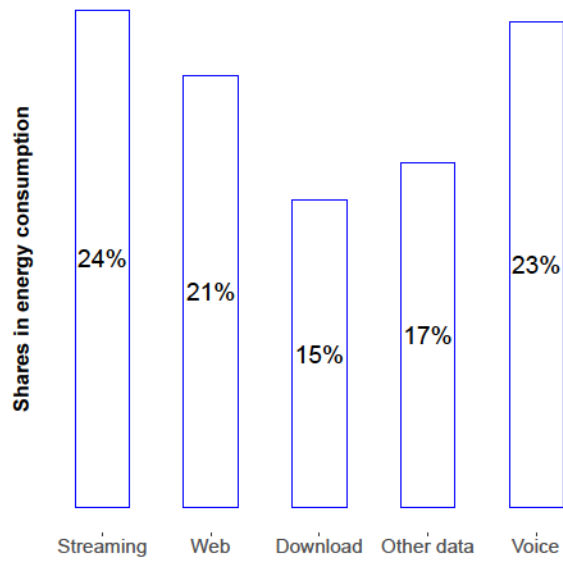


Figure 3.5: Shares in mobile core energy consumption: hybrid sharing.

traffic throughput.

Network equipment	Useful output	Number of players	Useful output proportions per service category				
			Streaming	Web	Download	Other data	Voice
Mobile Base stations	Data throughput	5	43%	31%	8%	16%	3%
DSLAM/OLT	Data throughput	4	63%	10%	12%	14%	0%
MSC	Subscriber	1	0%	0%	0%	0%	100%
SGSN	Simultaneously Attached Users	4	25%	25%	25%	25%	0%
GGSN	Paquets/s	4	43%	32%	9%	16%	0%
41 GGSN	Simultaneously Attached Users	4	25%	25%	25%	25%	0%
MME	Simultaneously Attached Users	4	25%	25%	25%	25%	0%
PGW/SGW	Paquets/s	4	45%	32%	8%	15%	0%
PGW/SGW	Simultaneously Attached Users	4	25%	25%	25%	25%	0%
HSS/AuC	Subscriber	5	20%	20%	20%	20%	20%
EIR	Mobile phones	5	20%	20%	20%	20%	20%
Ethernet switch	Data throughput	4	63%	10%	12%	14%	0%
IP router	Data throughput	5	59%	15%	11%	15%	0%
Streaming Server	Data throughput	1	100%	0%	0%	0%	0%

Table 3.3: Useful outputs



## Chapter 4

# Energy Efficiency of the Service Categories Delivered by a Mobile Access Network

### 4.1 Context and problem statement

Once we have shared the responsibility of service categories in the network energy consumption, this chapter aims at computing their energy efficiency. According to ETSI [31], the energy efficiency of a radio access network is the ratio of its traffic volume to its energy consumption.

Extending this definition, we introduce a new metric for computing the energy efficiency of service categories delivered by a radio access network, expressed in bits/imputed Joule. This metric should be valid for all services to be defined such as voice, data, video streaming, online gaming, etc, and for all possible architectures: classical reference architecture, centralized radio access, virtualized radio architecture, etc.

We define the energy efficiency of a service category to be the ratio of its traffic volume to its energy consumption.

We consider first a network equipment. The energy efficiency of a service category can be expressed as the ratio of its traffic throughput to its power consumption considering the mean traffic throughput and mean power consumption. We specifically consider 5 service categories: Streaming, Web, Download, other data services and Voice. We consider two cases: the case when the network equipment has no sleep mode feature and the case when it is put into sleep mode during idle periods, that is, periods of time the equipment has no packets. In the former, we use our Shapley-based model introduced previously to assign a share of the fixed power consumption to each service category and then derive the energy efficiency. In the latter, the power consumed by the equipment irrespective of traffic is the average of the fixed power consumed when it is active and the power consumed when it is in sleep mode. We give its analytical expression, and so, introduce a new sharing model, also based on

the Shapley value, whose characteristic function is consistent with this expression. This sleep-mode-oriented Shapley-based sharing model is also a trade-off as compared to uniform and proportional approaches, which is an appreciable outcome.

Moreover, we consider a radio access network. We consider two scenarios, one scenario where some service categories are mandatory, it is typically the case of Voice which is mandatory to be provided due to legal constraints, and another one where there is no mandatory service categories. We use our Shapley-based model to assign a share of the fixed energy consumption to each service category, and derive the energy efficiency.

We also discuss the conditions to not deteriorate the energy efficiency of a radio access network over time. At constant capacity, energy efficiency increases with load due to the amortization of the fixed energy consumption. As traffic increases, the fixed component gets amortized and the network energy efficiency is improved.

Upgrading the network based on long term previsions (five years for example) typically results in a higher increase in energy consumption than in traffic, at least for a while after the upgrade operation, which typically consists in adding additional equipment in the network. Because of this, the energy efficiency of the network goes upward and downward as it decreases after an upgrade then increases with the load until the next upgrade operation.

Newer technologies are typically more energy efficient than older ones, they come with better software, algorithms, etc. On the field however, the network is not operated at full load, i.e., at maximum capacity, and so, the newer technologies are not necessarily more energy efficient. For instance, deploying a 4G network alongside the existing 3G network may result in a less energy efficient network since traffic is shared between the two technologies.

We specifically focus on the two ways mostly used for upgrading network capacity: either by adding equipment with the same technology, for instance adding 4G sites in a 4G network, or by deploying equipment with another technology, typically more recent and more efficient like adding LTE-A sites in a LTE network. In each case, we determine the maximum number of sites to be added so that the upgrade does not deteriorate the network energy efficiency over time.

The remainder of this chapter is organized as follows. In section 4.2, we review some literature related to the energy efficiency of mobile networks and services. In section 4.3, we consider a radio access equipment and discuss the energy efficiency of service categories. In section 4.4, we consider a radio access network and discuss the energy efficiency of service categories. In section 4.5, we investigate the conditions to not deteriorate the network energy efficiency over time. Section 4.6 eventually concludes the chapter.

## 4.2 Related work

In [46, 47, 48, 49, 50, 51, 52], the authors survey the state-of-the-art addressing energy efficiency in wireless access networks.

Greenberg et al. in [53] examine the costs of cloud service data centers. The authors defined the cost in terms of work completed per dollar invested. They notice that this cost is most of the time high because resources inside the data



centers often operate at low utilization due to resource stranding and fragmentation. This recall the importance of amortizing the fixed energy consumption of equipment to reduce the energy cost as discussed in this chapter. In our work, we consider the energy cost of network equipment instead. In [54, 55, 56, 57, 58, 59], the authors assess the energy-per-bit of network equipment. They give methods and tools for optimizing the equipment energy-per-bit. However, these investigations do not consider the energy efficiency aspects of services. This chapter goes in this direction.

In [60, 61, 62, 63, 64, 65], the authors discuss the energy-aware management of mobile access networks and recommend notably load adaptive techniques such as sleep mode in order to optimize the amount of energy that can be saved by reducing the number of active cells during the periods when they are not necessary because traffic is low. Saker et al. [63] show that dynamic real-time sleep mode outperforms static sleep mode. In our work, we consider the former. Energy savings due to sleep mode stem from the reduction of the power consumed by the network irrespective of traffic. We discuss the analytical expression of this power in this chapter.

In [66, 67, 68, 69, 70, 71], the authors discuss how to upgrade a network while improving its spectral and energy efficiencies. It is showed that network densification is reaching a fundamental limit as the signal-to-interference-plus-noise ratio (SINR) decreases monotonically with density in dense networks. Some authors recommend to densify the network with indoor small cells mainly, while maintaining some outdoor coverage for high-speed outdoor users. Some works show that in scenarios with full load, the deployment of micro base stations has a rather moderate effect on the power consumption of a cellular network. These works recommend to upgrade the network with small cells in order to improve its spectral and energy efficiency. In this chapter, we discuss how to upgrade a mobile access network with the same radio technology or with a more recent one, typically more spectral and energy efficient, without deteriorating its energy efficiency over time.

## 4.3 Energy efficiency of service categories delivered by a radio access equipment

### 4.3.1 Model

As stated earlier, the power consumption  $P$  of a network equipment can be modeled as a linear function of the load. It is given by:

$$P(\rho) = P_f + (P_{max} - P_f)\rho \quad (4.1)$$

where  $\rho$  is the load of the equipment (it is a fraction of the equipment maximum throughput),  $P_f$  is the fixed power consumption which is consumed irrespective of traffic and  $P_{max}$  its maximum power consumption which is consumed at full load, i.e.,  $P_{max} = P(\rho = 1)$ .

The power consumption of a network equipment is then composed of a fixed component  $P_f$  and a variable component  $P_v = (P_{max} - P_f)\rho$ .

Let  $\beta_i$  denote the energy efficiency of service category  $i$ , that is, the amount of bits of service category  $i$  transmitted per joule of energy. According to ETSI

[31], the energy efficiency of a network equipment is the ratio of its traffic volume to its energy consumption. We extend this definition and define the energy efficiency of a service category to be the ratio of its traffic volume to its energy consumption. Considering the mean traffic throughput and mean power consumption, the energy efficiency of a service category can be expressed as the ratio of its traffic throughput to its power consumption. And so,

$$\beta_i = \frac{d_i}{P_i} \quad (4.2)$$

where  $d_i$  is service category  $i$  traffic throughput and  $P_i$  is its power consumption.

$$P_i = \varphi_i P_v + x_i P_f \quad (4.3)$$

where  $\varphi_i$  is the traffic proportion of service category  $i$ , and  $x_i$  it shares in the fixed power consumption we determine with the Shapley value.

### No sleep mode

In this scenario, the equipment is not put into sleep mode during idle periods.

Let model 1 denote our Shapley-based model introduced in chapter 2.

The share of service category  $i$  in the fixed power consumption using model 1 is given by  $x_i = \phi_i$ , with:

$$\phi_i = \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) \varphi_i + \left( \sum_{s=2}^N \frac{(\binom{N-1}{s-2} - \binom{N-1}{s-1}) \binom{N-2}{s-2}}{\binom{N-1}{s-1} \binom{N-1}{s-2} s \binom{N}{s}} \right) (1 - \varphi_i) \quad (4.4)$$

where  $N$  is the number of service categories.

The power consumption of service category  $i$  is given by:

$$P_i = \varphi_i P_v + \phi_i P_f \quad (4.5)$$

### Case with sleep mode feature

We consider in our work the possibility of putting an equipment into sleep whenever it has no packet to serve. In this case, the power consumed during these idle periods is less than  $P_f$  as some components are switched off. Let  $P_{SM}$  denote the power consumed during idle periods.

When the equipment is put into sleep mode during idle periods, the power  $\bar{P}_f$  consumed irrespective of traffic is the average of the fixed power consumed when it is active and power consumed when it is in sleep mode. Then,

$$\bar{P}_f = P_f \pi(\{active\}) + P_{SM} \pi(\{SM\}) \quad (4.6)$$

Let us consider the equipment to be a M/M/1 queuing system with Poisson arrivals with rate  $\lambda$  and exponential service with rate  $\mu$ . Then,

$$\pi(\{active\}) = \rho \quad (4.7)$$

and

$$\pi(\{SM\}) = 1 - \rho \quad (4.8)$$

We derive,

$$\bar{P}_f = P_{SM} + (P_f - P_{SM})\rho \quad (4.9)$$

So, the power consumed irrespective of traffic regarding coalition  $S$  is given by:

$$V(S) = P_{SM} + (P_f - P_{SM})\rho_S \quad (4.10)$$

where  $\rho_S$  is the traffic load of coalition  $S$ .

Let  $T$  denote a coalition containing service category  $i$ , service category  $i$  marginal contribution in  $T$  is given by  $\delta(\{i\}) = V(T) - V(T \setminus \{i\})$ , so

$$\delta(\{i\}) = (P_f - P_{SM})\rho_i \quad (4.11)$$

except for the coalition  $\{i\}$  where

$$\delta(\{i\}) = P_{SM} + (P_f - P_{SM})\rho_i \quad (4.12)$$

as  $V(\emptyset) = 0$ .

The Shapley value  $SV_i$  of service category  $i$  is the mean of its marginal contributions in all the scenario of constructing the grand coalition.

Based on Eqn. (2.10),

$$SV_i = \frac{(N-1)!}{N!} (P_{SM} + (P_f - P_{SM})\rho_i) + \frac{(N-1)!(N-1)}{N!} ((P_f - P_{SM})\rho_i) \quad (4.13)$$

We derive

$$SV_i = \frac{P_{SM}}{N} + (P_f - P_{SM})\rho_i \quad (4.14)$$

Let denote  $\phi'_i$  the share of service category  $i$  in the power consumed irrespective of traffic. It is given by:

$$\phi'_i = \frac{\frac{P_{SM}}{N} + (P_f - P_{SM})\rho_i}{\bar{P}_f} \quad (4.15)$$

$x_i = \phi'_i$  and so, the power consumption of service category  $i$  is given by:

$$P_i = \varphi_i P_v + \phi'_i \bar{P}_f \quad (4.16)$$

Let model 2 denote the scenario with sleep mode.

### 4.3.2 Numerical applications

We consider a 4G base station whose distribution of traffic is depicted in Fig. 4.1, based on a real dataset extracted from an operational network in Europe. Traffic on the equipment is classified into 5 service categories: Streaming, Web, Download, other data services and Voice.

Tab. 4.1 summarizes the parameters of the system, based on [72, 10]. We consider a maximum power of 742.2 Watts, a fixed power of 138.9 Watts, a downlink capacity of 72 Mbps, an uplink capacity of 12 Mbps. According to [72], a base station can feature several sleep modes. We consider, again, one

Table 4.1: Base station parameters

Parameters	Values
Maximum power (Watt)	742.2
Fixed power (Watt)	138.9
Sleep mode power (Watt)	86.3
Capacity (Mbps)	72 DL, 12 UL

sleep mode and we assume that it consumes as much power consumption as the shortest sleep mode discussed by the authors, that is  $P_{SM} = 86.3$  Watts. A base station has different parameters in downlink and uplink directions. Uplink accounts for 20% of total traffic, based on [73] and measurements carried out on the above-mentioned real operator network, and 13% of total power consumption according to [10, 11]. We focus in this work on the uplink direction. The methodology remains valid for the downlink.

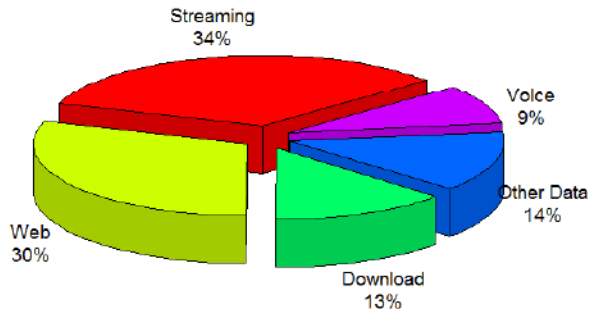


Figure 4.1: Traffic proportions of the service categories.

### 4.3.3 4G base station without sleep mode feature

Fig. 4.2 shows the energy efficiency of the 5 service categories based on our Shapley-based model 1 alongside with uniform and proportional approaches.

A proportional sharing of the fixed power consumption amounts to considering that all the service categories have the same energy efficiency whatever their traffic volumes, while an equal sharing results in a better energy efficiency for service categories having a high traffic volume as compared to those having a lower traffic volume.

Energy efficiencies resulting from the Shapley-based model lie between those of uniform and proportional approaches. This is an expected outcome as the Shapley-based model 1 is a trade-off between uniform and proportional sharing.

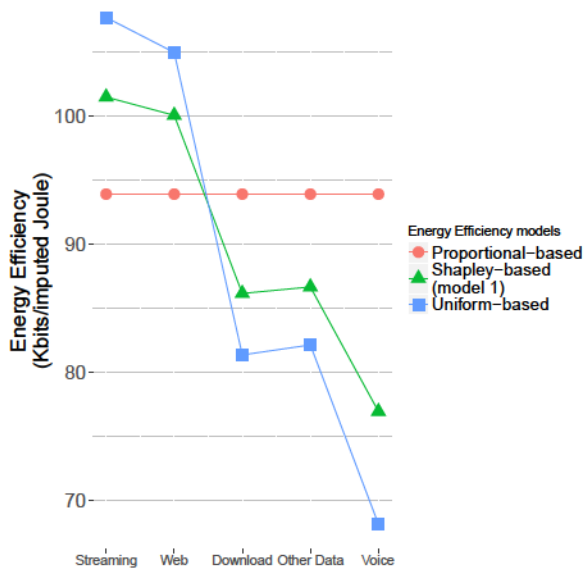


Figure 4.2: Energy efficiency of service categories - case without sleep modes.

#### 4.3.4 4G base station with sleep mode feature

When the equipment is put into sleep mode during idle periods, we compute the energy efficiency of the service categories based on model 2.

Fig. 4.3 shows the shares of the service categories in the power consumed irrespective of traffic, based on uniform sharing, proportional sharing and Shapley-based model 2. We notice that model 2 is also a compromise among the service categories, and this is an appreciable outcome. It ranges between a uniform sharing and a proportional sharing according to the sleep mode power consumption. It is similar to a uniform sharing when the sleep mode power consumption equals the fixed power consumption. It is similar to a proportional sharing when the equipment consumes no power in sleep mode.

Fig. 4.4 shows the energy efficiency of the service categories in the case with sleep mode. We notice that the energy efficiency is improved because of the sleep mode.

### 4.4 Energy efficiency of service categories delivered by a radio access network

#### 4.4.1 Energy efficiency models

In this section, we consider a radio access network and compute the energy efficiency of the service categories it delivers. Again, we define the energy efficiency of a service category as the ratio of its traffic volume to its energy consumption. This metric is expressed in bits/imputed Joule.

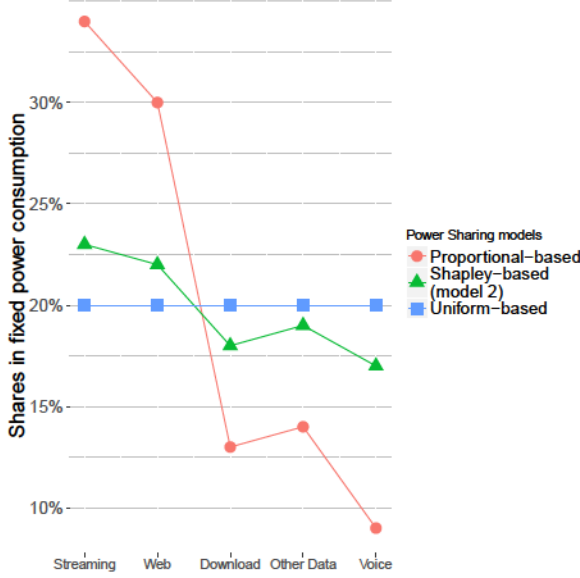


Figure 4.3: Shares in the fixed power consumption.

Let  $\beta_i$  denote the energy efficiency of service category  $i$ ,

$$\beta_i = \frac{v_i}{E_i} \quad (4.17)$$

where  $v_i$  is the traffic volume of service category  $i$ , and  $E_i$  is its energy consumption. The traffic volume of service category  $i$  comes from measurements carried out on the investigated network by the network operator. As of the energy consumption, it derives from our Shapley-based model introduced in chapter 2.

As stated earlier, the energy consumed by the radio access network is composed of a variable and a fixed component, denoted by  $E^v$  and  $E^f$ , respectively.

Each service category is assigned a share of the variable energy consumption equal to its traffic proportion since this energy component is load-dependent. So,

$$E_i^v = \varphi_i \times E^v \quad (4.18)$$

where  $E_i^v$  is the variable energy consumption of service category  $i$  and  $\varphi_i$  is its traffic proportion.

Let  $\phi_i$  denote the share of service category  $i$  in the fixed energy consumption, thus we have:

$$E_i^f = \phi_i \times E^f \quad (4.19)$$

where  $E_i^f$  is the fixed energy consumption of service category  $i$ .

In the case without mandatory player, the share of service category  $i$  is given by:

$$\phi_i = \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) \varphi_i + \left( \sum_{s=2}^N \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-2}{s-2}}{(\binom{N-1}{s-1}) (\binom{N-1}{s-2}) s \binom{N}{s}} \right) (1 - \varphi_i)$$



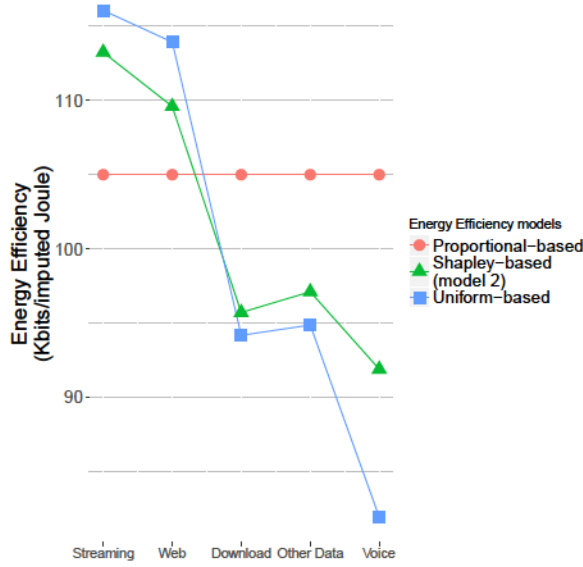


Figure 4.4: Energy efficiency of service categories - case with sleep mode.

When there is a mandatory player, the share of the mandatory player is given by:

$$\phi_{i^*} = \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) \varphi_{i^*} + \left( \sum_{s=2}^N \frac{\binom{N-2}{s-2}}{\binom{N-1}{s-1} s \binom{N}{s}} \right) (1 - \varphi_{i^*})$$

where subscript  $i^*$  stands for the mandatory player.

The share of a non-mandatory player is given by:

$$\begin{aligned} \phi_o = & \left( \sum_{s=2}^N \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-2}{s-2}}{(\binom{N-1}{s-1}) (\binom{N-1}{s-2}) s \binom{N}{s}} \right) \varphi_{i^*} + \left( \sum_{s=2}^N \frac{\binom{N-2}{s-2}}{(\binom{N-1}{s-1}) s \binom{N}{s}} \right) \varphi_o \\ & + \left( \sum_{s=3}^N \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-3}{s-3}}{(\binom{N-1}{s-1}) (\binom{N-1}{s-2}) s \binom{N}{s}} \right) (1 - \varphi_{i^*} - \varphi_o) \end{aligned}$$

where subscript  $o$  stands for a non-mandatory player.

Based on these models, we compute and analyze the energy efficiency of service categories.

#### 4.4.2 Numerical applications

We now run numerical applications with our models for computing the energy efficiency of service categories delivered by a radio access network. We consider a real operational European network. The period of the study covers two years, representing a mature 2G/3G network with early LTE deployments and associated traffic increase. We measure all voice and data services that are transmitted in the network with the following classification of services: two large ones, namely streaming and web browsing, and three smaller ones: download,

voice and other data services. Fig. 2.4 shows their traffic proportions as taken from the real data set. We consider only traffic and energy consumption of the 3G/UMTS sub-network.

Fig. 4.5 shows the energy efficiency of the service categories. In the figure, we consider two scenarios: one scenario where all the service categories are optional, i.e., none of them is obliged to be delivered, and another scenario where Voice is mandatory. Naturally, Voice is more energy efficient when it is optional since its contribution in the fixed energy consumption is 15% instead of 29%. Let us note that the energy efficiency of a service category is an increasing function of its traffic proportion. So, service categories having a large traffic volume such as Streaming and Web are more energy efficient than those having a small traffic volume such as Download, Voice and other data services. Data services are further more energy efficient when Voice is a mandatory player.



Figure 4.5: Energy efficiency of service categories.

## 4.5 How to not deteriorate a mobile network energy efficiency undergoing network upgrades

### 4.5.1 Energy consumed per transmitted bit

The energy-per-bit of the network, which we denote by  $\alpha$ , is the amount of energy consumed by the network to transmit one bit, and is expressed in (Joules/bit). It is the inverse of energy efficiency which is expressed in (bits/Joule). Let  $\Delta t$  denote the observation period of the network;  $\Delta t = t_2 - t_1$ , with  $t_1$  and  $t_2$  the initial and final instants of observation, respectively. Again, the energy efficiency of a radio access network is the ratio of its traffic volume to its energy

consumption according to ETSI, and so, the energy-per-bit over  $\Delta t$  is given by:

$$\alpha = \frac{\int_{t_1}^{t_2} P(t) dt}{v} \quad (4.20)$$

where  $v$  is the traffic volume measured on the network over  $\Delta t$  (in units of (Giga)bits) and  $P(t)$  is the instantaneous power consumption of the network, which consists, as stated earlier, of a fixed component (independent of traffic) and a variable one (load-dependent).

According to [10], the power consumption of a network equipment can be modeled as a linear function of the load, that is:

$$P(t) = P_f + \rho(t)(P_{max} - P_f) \quad (4.21)$$

where  $P_f$  is the fixed power consumption,  $\rho(t)$  is the load at time  $t$  and  $P_{max}$  is the maximum power.

In addition, when considering the mean traffic rate, the traffic volume can be expressed as follows:

$$v = R \times \Delta t \quad (4.22)$$

where  $R$  is the mean traffic rate (in units of (Mega)bits per second). So,

$$\alpha = \frac{1}{\Delta t} \frac{\int_{t_1}^{t_2} P_f + \rho(t)(P_{max} - P_f) dt}{R} \quad (4.23)$$

$$\alpha = \frac{P_f}{R} + \rho \frac{P_{max} - P_f}{R} \quad (4.24)$$

where  $\rho = \frac{1}{\Delta t} \int_{t_1}^{t_2} \rho(t) dt$  is the mean load over  $\Delta t$ .

Moreover,

$$\rho = \frac{R}{C} \quad (4.25)$$

where  $C$  is the network capacity (also in (Mega)bits per second).

And so, Eqn. (4.24) becomes,

$$\alpha(R, C) = \frac{P_f}{R} + \frac{P_{max} - P_f}{C} \quad (4.26)$$

#### 4.5.2 Energy efficiency versus traffic rate

The variation of energy-per-bit versus traffic rate at constant capacity is given by:

$$\frac{\partial \alpha(R, C)}{\partial R} = -\frac{P_f}{R^2} \quad (4.27)$$

As illustrated in Eqn. (4.27), energy-per-bit is a decreasing function of the traffic rate at constant capacity given that  $\frac{\partial \alpha(R, C)}{\partial R} < 0$ , and so, the energy efficiency is an increasing function of the traffic rate at constant capacity.

Thus, a traffic rate increase improves the network energy efficiency as long as this increase does not call for a network upgrade. When a network upgrade is operated, this rule might be upset, and we study next the impact of an upgrade on the energy efficiency of the network.

Table 4.2: eNodeB parameters

Parameters	Definition	Typical values
$K$	Number of sites	
$P_{max}^{bs}(Watt)$	Maximum power	528
$P_f^{bs}(Watt)$	Fixed power	333
$C^{bs}(Mbps)$	Base station capacity	72 DL, 12 UL
$R$	Traffic rate	

### 4.5.3 Upgrading a radio access network

We consider a real operational 4G access network composed of 10000 eNodeBs and an average traffic rate of 10 Gbps. Tab. 4.2 summarizes the parameters of the network equipment. Column 3 gives the typical mean values of the maximum power, fixed power and capacity of an eNodeB. We assume that the uplink accounts for 20% of the total traffic, based on [73] and on measurements carried out on the above-mentioned real network by the network operator, and it accounts for 13% of the total power consumption [10, 11].

#### Energy efficiency of service categories

We assume that the network equipment have the same mean capacity, maximum power and fixed power. Then, the total mean capacity of the network is the mean capacity of an equipment multiplied by the number of sites in the network. It applies also to the maximum and fixed powers. Hence,  $P_{max} = KP_{max}^{bs}(T)$ ,  $P_f = KP_f^{bs}(T)$  and  $C = KC^{bs}(T)$  where  $P_{max}^{bs}(T)$ ,  $P_f^{bs}(T)$  and  $C^{bs}(T)$  are respectively the maximum power, fixed power and mean capacity of a site.  $T$  denotes the radio technology. In the sequel, we use the terms base station and site interchangeably.

Based on Eqn. (4.26), the energy-per-bit of the network is given by:

$$\alpha(R, K, T) = \frac{P_{max}^{bs}(T) - P_f^{bs}(T)}{C^{bs}(T)} + P_f^{bs}(T) \frac{K}{R} \quad (4.28)$$

For clarity sake,  $T$  will be omitted in the sequel. Eqn. (4.28) shows that energy efficiency (inverse of energy-per-bit) is an increasing function of the traffic and a decreasing function of the number of sites. But the network energy efficiency cannot be increased indefinitely as the traffic should not exceed a threshold  $R_{threshold}$ , at constant capacity. We derive from Eqn. (4.25):

$$R_{threshold} = KC^{bs} \rho_{threshold} \quad (4.29)$$

where  $\rho_{threshold}$  is a given network load threshold obeying operational constraints.

Eqns. (4.28) and (4.29) yield a lower bound on the network energy-per-bit at constant capacity, termed  $\alpha_{min}$ .

$$\alpha_{min} = \frac{P_{max}^{bs} - P_f^{bs}}{C^{bs}} + \frac{P_f^{bs}}{C^{bs} \rho_{threshold}} \quad (4.30)$$

The access network has different characteristics in the uplink and downlink, so all the above expressions should be considered separately in both directions. The network under study has an uplink-energy-per-bit of  $200 \mu J/bit$  based on Eqn. (4.28), i.e., the uplink radio resources consume on average  $200 \mu J$  per transmitted bit. According to [10], the observed traffic for uploading a 5-MB photo to Facebook in normal quality using a smartphone with Wifi and 4G technologies is about 1.1 MB, because Facebook compresses photos heavily in user browser before sending them to Facebook servers. Uploading a 5-MB photo to Facebook in normal quality costs about 0.5 Wh. If the network were loaded at half of its capacity, then this cost would be reduced to 0.02 Wh, since the energy-per-bit would be  $9.3 \mu J/bit$  based on Eqn. (4.30). This would correspond to 96% of energy gain. Thus, loading the network even only at half of its capacity allows significant energy savings, unlike the actual operation of networks which are most of the time under-loaded. So, load adaptive techniques or network infrastructure sharing are good candidates to reduce network energy consumption.

Let us consider a network upgrade with the same technology in order to keep up with a traffic increase proportion of  $z$ . Let  $K_f^{max}$  denote the maximum number of sites in the upgraded network which does not deteriorate energy efficiency over time. We have:

$$K_f^{max} = (1 + z) \times K_i \quad (4.31)$$

where  $K_i$  is the number of sites in the network to be upgraded.

Eqn. (4.31) results from the resolution of  $\alpha(R_f, K_f) \leq \alpha(R_i, K_i)$ , i.e., the energy-per-bit of the upgraded network should be lower than or equal to the energy-per-bit of the initial network. So, the maximum number of sites that can be added in the network without deteriorating its energy efficiency is proportional to traffic increase. It is worth to note that this result does not take into consideration spectral efficiency constraints, and it is up to the network designer to consider both our results along with other network constraints in the upgrade policy.

Next, we consider a network upgrade with a more recent technology.

### LTE network swap

A swap consists in replacing the sites of the network by newer, more efficient ones. We discuss the conditions under which a swap operation does not degrade the energy efficiency of the network. We propose to investigate the swap of LTE sites by LTE-A ones. The energy efficiency of network equipment typically improves with the technology. Thus, an LTE site is less energy efficient than an LTE-A site at full operating load. But in practice, networks are typically under-loaded, and so, an LTE-A network is not necessarily more energy efficient than an LTE network. Hence the need to study the conditions for a swap operation not to degrade energy efficiency.

Let  $x$  denote the ratio of an LTE-A site fixed power consumption to an LTE site fixed power consumption. In this work, we assume the special case when this ratio is the same regarding the maximum power consumptions. Further investigations will consider a more general case. We consider values of  $x$  ranging from 0.5 to 1.5 depending on the network configuration. When  $x = 1$ , an LTE-A



site consumes as much power as an LTE site. We compare the power consumptions at equal load; the load being a fraction of the maximum throughput of the equipment.

In the simple case when the network operator makes a swap operation consisting in replacing each LTE site by a LTE-A site, at constant traffic, the network energy efficiency is not deteriorated when a LTE-A site consumes at most as much power as a LTE site.

In the case when the LTE sites are no longer necessarily replaced by an equal number of LTE-A sites, the maximum number of LTE-A sites in the upgraded network which does not deteriorate its energy efficiency is given by:

$$K_f^{max}(x, y, z) = \frac{1+z}{x} K_i + (1+z) \left( \frac{1}{x} - \frac{1}{y} \right) \left( \frac{P_{max}^{bs}}{P_f^{bs}} - 1 \right) \frac{R_i}{C^{bs}} \quad (4.32)$$

with  $x > 0$ ,  $y > 1$ .

Eqn. (4.32) comes from the resolution of  $\alpha(R_f, K_f) \leq \alpha(R_i, K_i)$ , i.e., the energy-per-bit of the upgraded network should be lower than or equal to the energy-per-bit of the initial network. Let us notice that the maximum number of LTE-A sites is a linear function of the number of LTE sites to be replaced whose slope is the ratio of the traffic increase to the power consumption increase. So, one can have more LTE-A sites in the network when traffic increases faster than power consumption. This may be a good outcome if many LTE-A sites are required to deal with QoS constraints.

Fig. 4.6 shows the maximum number of sites in the upgraded network which does not degrade energy efficiency. We consider 23% traffic increase (according to Cisco [74]), i.e.,  $R_f = 1.23R_i$ . We set  $y = 10$  as LTE-A is supposed to increase the theoretical LTE base station throughput by a factor of 10.

Please note that replacing the LTE sites by a lower number of LTE-A sites would not result necessarily in coverage holes in the network since the LTE-A sites may transmit at higher power and thus have higher coverage.

### Proportion of LTE-A sites in the upgraded network

In this section, we replace some LTE sites with LTE-A sites. The objective is to find the right proportion of LTE-A sites in the upgraded network to not deteriorate energy efficiency.

Resolving the inequality  $\alpha(R_f, K_f) \leq \alpha(R_i, K_i)$ , i.e., the energy-per-bit of the upgraded network should be lower than or equal to the energy-per-bit of the initial network, we get:

$$\begin{aligned} & \frac{(1-x)(1-y)K_f C^{bs} P_f^{bs}}{zR_i} \theta^2 + \left( \left( \frac{xK_f}{z} - K_i \right) \frac{1-y}{R_i} \right. \\ & \quad \left. + \frac{(1-x)yK_f}{zR_i} \right) C^{bs} P_f^{bs} + (y-x)(P_{max}^{bs} - P_f^{bs}) \theta \\ & \quad + \left( \left( \frac{xK_f}{z} - K_i \right) \frac{yC^{bs} P_f^{bs}}{R_i} + (x-y)(P_{max}^{bs} - P_f^{bs}) \right) \leq 0 \quad (4.33) \end{aligned}$$

where  $\theta$  is the proportion of LTE sites in the upgraded network.

Let us consider 23% traffic increase according to Cisco [74]. Fig. 4.7 shows the left-hand side of (4.33). The minimum proportions of LTE sites in the



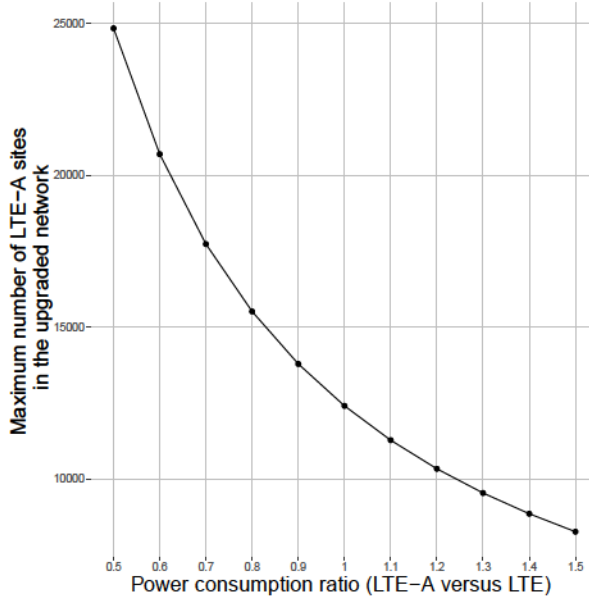


Figure 4.6: Maximum number of sites in the upgraded network (LTE-A sites) to avoid degrading the network energy efficiency

upgraded network which do not deteriorate energy efficiency are the values of  $\theta$  for which the curves are negatives. For example, when an LTE-A site consumes 30% more power than an LTE site, i.e.,  $x = 1.3$ , the operator should keep at least 20% of LTE sites in the upgraded network.

## 4.6 Conclusion

In this chapter we first introduced how to compute the energy efficiency of service categories delivered by a network equipment. We classified the services into 5 categories: Streaming, Web, Download, other data services and Voice. Extending the ETSI definition of a mobile access equipment energy efficiency [31], we defined the energy efficiency of a service category to be the ratio of its traffic volume to its energy consumption which we expressed as the ratio of traffic throughput to power consumption considering the mean traffic throughput and mean power consumption. We assigned a share of the equipment power consumption to each service category with our Shapley-based model introduced in chapter 2. We also considered the case when the equipment is put into sleep mode during idle periods. We introduced the analytical expression of the power consumed by the equipment irrespective of traffic in this scenario and assigned it to the service categories using a new Shapley-based model whose characteristic function is consistent with this expression.

Then, we computed the energy efficiency of service categories delivered by a mobile access network. We used our Shapley-based model introduced in chapter 2 to assign a share of the network energy consumption to each service category and derived the energy efficiency. We considered two scenarios: one scenario

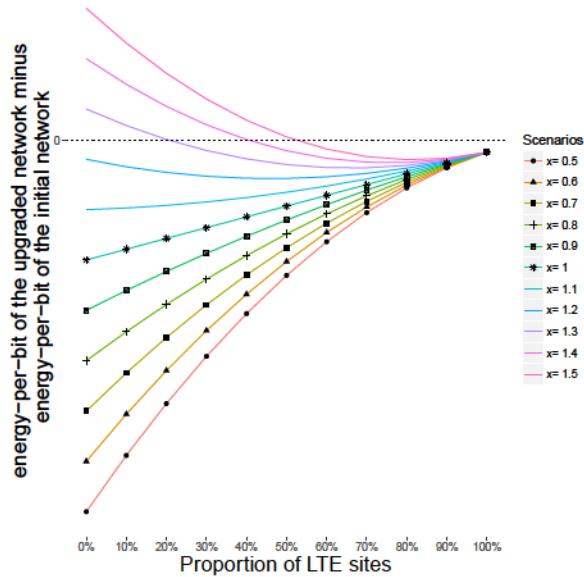


Figure 4.7: Energy-per-bit of the upgraded network minus energy-per-bit of the LTE network versus the proportion of LTE sites, case with 23% traffic increase

where Voice is mandatory to be provided, in line with what happens typically in real operated networks, and another one without mandatory players. The mandatory nature of a player degrades its energy efficiency as its share in the network energy consumption gets increased.

Moreover, we discussed the conditions to not deteriorate the energy efficiency of a mobile access network undergoing upgrade operations over time. We considered two approaches for upgrading a network: either adding sites with the same technology or adding sites implementing another technology, typically more recent and more efficient. In both cases, we derived the maximum number of sites to be added in the network so as to not deteriorate its energy efficiency. We showed that a network loaded even at only half of its capacity allows significant energy saving, nearly 95% for a photo upload on Facebook regarding the network under study. Given that operated networks are typically under-loaded, operators should closely consider techniques for adapting network capacity to load. Eventually, we investigated the right mix between sites implementing different technologies in the network, from an energy efficiency point of view. Because the validity of these models does not rely on any particularity of the mobile access network, they are applicable to other network segments.

## Chapter 5

# Conclusion and perspectives

### 5.1 Conclusion

We investigated in this thesis how to share the responsibility of service categories in the fixed energy consumption of a network.

We classified the services based on criteria such as traffic, originating service providers and/or devices. Based on traffic, we segmented the services into 5 categories, namely, Streaming, Web, Download, other data services and Voice.

Based on field measurements and works in the literature, the network energy consumption is composed of a variable and a fixed components. The former is consumed to serve traffic unlike the latter which is consumed irrespective of traffic. The share of a service category in the variable energy consumption is equal to its traffic proportion as this energy component is load-dependent. As of the fixed energy consumption, it may seem rational to assign it equally to the service categories as it is consumed irrespective of traffic, however, this does not take into account the fact that this energy component increases with traffic over time due to network upgrade operations, and so, it is somehow related to services. Because of this, we proposed to use the Shapley value to assign to each service category a share in the fixed energy consumption based on its impact on this increase.

First, we considered a radio access network and shared the responsibility of service categories in the fixed energy consumption based on our Shapley-based model. An appreciable outcome of the Shapley-based model is that it is a trade-off in the sense that shares of service categories having a large traffic volume are lowered as compared to a sharing proportional to traffic (proportional sharing), and so are shares of service categories having a low traffic volume as compared to an equal sharing (uniform sharing). Given the computational complexity of the Shapley value, we proposed a closed-form expression for computing the shares of service categories with less computational complexity. We also studied the case when some service categories are mandatory to be provided, as it is typically the case for Voice due to legal constraints. The Shapley-based model reflects the mandatory nature of Voice by increasing its share in the fixed energy consumption, reducing consequently shares of data services. The Shapley-based model is similar to a proportional sharing when there are only 2 service categories and none of them is mandatory. When all the service categories have the same traf-

fic proportions or are considered to be mandatory, the model is equivalent to a uniform sharing. We also showed that the Shapley-based model is impacted by the number of service categories; Impact of service categories having a marginal traffic is maximum for 5 categories and minimum for 2 categories. To close the first part of our work, we shared the responsibility of service categories in the fixed energy consumption of heterogeneous networks with upgrade operations over time. In this regard, we applied our Shapley-based model per radio technology and upgrade level. We considered the cases when the Shapley-based model is applied to traffic volumes or to traffic increase. The former puts the weight on service categories having a large traffic volume, and the latter on those having a high traffic increase.

Moreover, we shared the responsibility of service categories in the energy consumption of a end-to-end network. In this investigation, we took into consideration all the blocks of the network, that is, the mobile access, the fixed access, the collect, the IP core, the mobile core, the registers and the service platforms. For each block, we assigned to each service category a share in the fixed energy consumption with our Shapley-based model. We considered three scenarios: when our Shapley-based model is applied to traffic, when it is applied to useful outputs and when it is applied to both traffic and useful outputs. The last two scenarios impact only the service categories shares regarding the mobile core as compared to the first one. We found that Streaming is the service category that consumes the most whatever the network block, except for the registers whose energy consumption is equally distributed over the service categories.

Finally, we introduced a metric for computing the energy efficiency of service categories. Extending the ETSI definition of the energy efficiency of a mobile access equipment [31], we defined the energy efficiency of a service category to be the ratio of its traffic volume to its energy consumption. We first considered a base station. We expressed the energy efficiency of a service category as the ratio of its traffic throughput to its power consumption considering the mean power consumption and mean traffic throughput. In the case when the base station has no sleep mode feature, we assigned to each service category a share in the power consumption with our Shapley-based model. Then, we considered the case when the base station is put into sleep mode and give the analytical expression of the power consumed irrespective of traffic in this scenario, and so, we defined a new Shapley-based model whose characteristic function is consistent with this expression. Furthermore, we considered a radio access network and conducted the same study. We considered a scenario where no service category is mandatory to be provided and another one where some service categories are mandatory, such as Voice due to legal constraints. When a service category is considered to be a mandatory player, it becomes less energy efficient as its share in the fixed energy consumption gets increased. Eventually, we discussed the conditions to not deteriorate the energy efficiency of a radio access network over time. We discussed the cases when the network is upgraded with the same radio technology and when it is upgraded with a new radio technology, typically more energy and spectral efficient. We showed that load adaptive techniques allow significant energy saving. Moreover, we computed the maximum number of additional sites for upgrading the network so as to not deteriorate its energy efficiency over time.



## 5.2 Perspectives

A possible follow up of our works could be the design of incentive mechanisms in order to incite end-users and service providers to adopt a greener behavior so as to reduce environmental and operational costs of networks. Models for computing the responsibility of end-users and service providers in the energy consumption of networks are key for building these mechanisms.

Our results are also valuable for designing fair pricing schemes. Let us consider 5G networks as an example. In order to optimize usage of the scarce radio spectrum, 5G comes with new connectivity schemes, namely, licensed shared access (LSA) and licensed assisted access (LAA). These connectivity schemes allow several mobile carriers to share a common radio spectrum which has a low usage rate, a military spectrum for example. In this regard, marketplace platforms are expected to arise for the demand and offer to meet. Our models would allow the design of auction mechanisms taking into account the energy cost of services expected to be provided.

In this work, we used traffic and useful outputs to assign to each service category a share in the end-to-end network fixed energy consumption. It would be interesting to discuss which one is best to be used. In addition, we discussed the energy efficiency of service categories delivered by a radio access network. It would be worth to conduct the same study considering other network segments, as well as the entire end-to-end network. In this case, parameters to be considered for computing the energy efficiency of service categories are not necessarily traffic. Furthermore, we did not consider in our analysis sleep mode activation and deactivation times and this would be an interesting study to undertake. Moreover, we considered a streaming server when sharing the responsibility of service categories in the energy consumption of a end-to-end network. One possible direction to go next is to consider all types of servers and Datacenters in the investigation for this to be as general as possible. Taking into account Datacenters in the analysis should allow discussing the impact of virtualization paradigms such as network function virtualization and Cloud-Radio Access Networks (C-RAN) on our models. As so-called telco Cloud is expected notably to bring low latency in networks, this is expected to spark deployment of new usages such as Internet of Things (IoT). A possible way to go would be to discuss the energy consumption and energy efficiency of IoT services.

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## Appendix A

# Closed-form expression for Shapley value of a player in the case without mandatory players

The characteristic function in the scenario without a mandatory player is as follows:

$$V(S) = \frac{\sum_{k_1=1}^s v_{k_1,S}}{\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1,S_{j_2}}}$$

where  $k_1$  spans over the member of a coalition, and  $j_2$  over coalitions of size  $s$ .

This characteristic function can be expressed as follows, that is:

$$V(S) = \frac{\varphi(S)}{\binom{N-1}{s-1}}$$

where  $\varphi(S)$  is the traffic proportion of coalition  $S$ , and  $s$  its size, i.e., the number of service categories in  $S$ .

To show this, it suffices to remember that there exists  $\binom{N-1}{s-1}$  coalitions of size  $s$  containing a given player, and so,  $\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1,S_{j_2}} = \binom{N-1}{s-1} v_T$ . Knowing that  $\sum_{k_1=1}^s v_{k_1,S} = v(S)$ , we get the result.

$v_T$ : total traffic volume,  $v(S)$ : traffic volume of coalition  $S$ .

The marginal contribution of player  $i$  in coalition  $S$  is the gain or loss of the coalition due to player  $i$ . It is determined as follows:

$$V(S) - V(S \setminus \{i\}) = \frac{\sum_{k_1=1}^s v_{k_1,S}}{\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1,S_{j_2}}} - \frac{\sum_{k_2=1}^{s-1} v_{k_2,S \setminus \{i\}}}{\sum_{j_4=1}^{\binom{N}{s-1}} \sum_{k_2=1}^{s-1} v_{k_2,S_{j_4}}}$$

Then,

$$\sum_{j_1=1}^{\binom{N-1}{s-1}} V(S_{j_1}) - V(S_{j_1} \setminus \{i\}) = \frac{\sum_{j_1=1}^{\binom{N-1}{s-1}} \sum_{k_1=1}^s v_{k_1, S_{j_1}, \{i\}}}{\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1, S_{j_2}}} - \frac{\sum_{j_1=1}^{\binom{N-1}{s-1}} \sum_{k_2=1}^{s-1} v_{k_2, S_{j_1} \setminus \{i\}}}{\sum_{j_4=1}^{\binom{N}{s-1}} \sum_{k_2=1}^{s-1} v_{k_2, S_{j_4}}}$$

$\binom{N-1}{s-1}$  is the number of coalitions of size  $s$  containing player  $i$ ,  $\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1, S_{j_2}}$  and  $\sum_{j_4=1}^{\binom{N}{s-1}} \sum_{k_2=1}^{s-1} v_{k_2, S_{j_4}}$  are respectively the traffic volumes of the coalitions of size  $s$  and  $s-1$ . They are constant for a given coalition size  $s$ , hence we can take them out of the sum over coalitions of the same size.

$\sum_{j_1=1}^{\binom{N-1}{s-1}} \sum_{k_1=1}^s v_{k_1, S_{j_1}, \{i\}}$  is the sum of the traffic volumes of the coalitions of size  $s$  containing player  $i$ .  $v_{k, S_j, \{i\}}$  is the traffic volume of the  $k^{\text{th}}$  element of the  $j^{\text{th}}$  coalition of size  $s$  containing player  $i$ . Player  $i$  belongs to all the  $\binom{N-1}{s-1}$  coalitions, while any other player belongs to  $\binom{N-2}{s-2}$  coalitions. In fact there are  $\binom{N-2}{s-2}$  coalitions of size  $s$  with both player  $i$  and a given player  $k$ .

$\sum_{j_1=1}^{\binom{N-1}{s-1}} \sum_{k_2=1}^{s-1} v_{k_2, S_{j_1} \setminus \{i\}}$  is the sum of the traffic volumes of the coalitions of size  $s-1$  not containing player  $i$ .  $v_{k, S_j \setminus \{i\}}$  is the traffic volume of the  $k^{\text{th}}$  element of the  $j^{\text{th}}$  coalition of size  $|S_j|$  not containing player  $i$ .  $|\cdot|$  is the cardinal function. Similarly, a given player  $k$  appears in  $\binom{N-2}{s-2}$  coalitions among the  $\binom{N-1}{s-1}$  coalitions of size  $s-1$ , derived from the  $\binom{N-1}{s-1}$  coalitions of size  $s$  containing  $i$ .

Then we have:

$$\sum_{j_1=1}^{\binom{N-1}{s-1}} V(S_{j_1}) - V(S_{j_1} \setminus \{i\}) = \frac{\binom{N-1}{s-1} v_i + \binom{N-2}{s-2} \sum_{\substack{k_3=1 \\ k_3 \neq i}}^N v_{k_3}}{\binom{N-1}{s-1} \sum_{k_4=1}^N v_{k_4}} - \frac{\binom{N-2}{s-2} \sum_{\substack{k_3=1 \\ k_3 \neq i}}^N v_{k_3}}{\binom{N-1}{s-2} \sum_{k_4=1}^N v_{k_4}}$$

$$\phi_i(v) = \frac{1}{N!} \sum_{s=1}^N (N-s)!(s-1)! \left( \frac{\binom{N-1}{s-1} v_i + \binom{N-2}{s-2} \sum_{\substack{k_3=1 \\ k_3 \neq i}}^N v_{k_3}}{\binom{N-1}{s-1} \sum_{k_4=1}^N v_{k_4}} - \frac{\binom{N-2}{s-2} \sum_{\substack{k_3=1 \\ k_3 \neq i}}^N v_{k_3}}{\binom{N-1}{s-2} \sum_{k_4=1}^N v_{k_4}} \right)$$

$$\binom{N}{s} = \frac{N!}{s!(N-s)!} \implies (N-s)!(s-1)! = \frac{N!}{s \binom{N}{s}}$$

Hence,

$$\phi_i(v) = \frac{1}{v_T} \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) v_i + \frac{1}{v_T} \left( \sum_{s=2}^N \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-2}{s-2}}{(\binom{N-1}{s-1}) (\binom{N-1}{s-2}) s \binom{N}{s}} \right) (v_T - v_i)$$

Let  $\varphi_i$  denote the traffic proportion of player  $i$ .

$$\varphi_i = \frac{v_i}{v_T}$$

$$\phi_i(N, p_i) = \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) \varphi_i + \left( \sum_{s=2}^N \frac{((\binom{N-1}{s-2}) - (\binom{N-1}{s-1})) \binom{N-2}{s-2}}{(\binom{N-1}{s-1}) (\binom{N-1}{s-2}) s \binom{N}{s}} \right) (1 - \varphi_i)$$

## Appendix B

# Case with a mandatory player

### B.1 Closed-form expression for Shapley value of the mandatory player

Let  $i^*$  denote the mandatory player. The value of a coalition with the mandatory player is :

$$V(S) = \frac{\sum_{k_1=1}^s v_{k_1, S}}{\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1, S_{j_2}}} \mathbf{1}_{i^* \in S}$$

The payoff of the mandatory player is :

$$\phi_{i^*}(v) = \frac{1}{N!} \sum_{s=1}^N (N-s)!(s-1)! \sum_{j_1=1}^{\binom{N-1}{s-1}} V(S_{j_1, \{i^*\}})$$

In fact  $V(S \setminus \{i^*\}) = 0 \forall S$

$$\sum_{j_1=1}^{\binom{N-1}{s-1}} V(S_{j_1, \{i\}}) = \frac{\sum_{j_1=1}^{\binom{N-1}{s-1}} \sum_{k_1=1}^s v_{k_1, S_{j_1, \{i\}}}}{\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1, S_{j_2}}}$$

$$\sum_{j_1=1}^{\binom{N-1}{s-1}} V(S_{j_1, \{i\}}) = \frac{\binom{N-1}{s-1} v_i + \binom{N-2}{s-2} \sum_{k_3=1, k \neq i^*}^N v_{k_3}}{\binom{N-1}{s-1} \sum_{k_4=1}^N v_{k_4}}$$

$$\phi_{i^*}(v) = \frac{1}{N!} \sum_{s=1}^N (N-s)!(s-1)! \frac{\binom{N-1}{s-1} v_{i^*} + \binom{N-2}{s-2} \sum_{k_3=1, k \neq i^*}^N v_{k_3}}{\binom{N-1}{s-1} \sum_{k_4=1}^N v_{k_4}}$$

Hence,

$$\phi_{i^*}(v) = \frac{1}{v_T} \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) v_{i^*} + \frac{1}{v_T} \left( \sum_{s=2}^N \frac{\binom{N-2}{s-2}}{\binom{N-1}{s-1} s \binom{N}{s}} \right) (v_T - v_{i^*})$$

The payoff of the mandatory player is given by:

$$\phi_{i^*}(N, p_{i^*}) = \left( \sum_{s=1}^N \frac{1}{s \binom{N}{s}} \right) p_{i^*} + \left( \sum_{s=2}^N \frac{\binom{N-2}{s-2}}{\binom{N-1}{s-1} s \binom{N}{s}} \right) (1 - p_{i^*})$$

## B.2 Closed-form expression for Shapley value of a non mandatory player in the case with a mandatory player

Let  $o$  denote a non-mandatory player. The payoff of  $o$  is given by:

$$\phi_o(v) = \frac{1}{N!} \sum_{s=1}^N (N-s)!(s-1)! \sum_{j_3=1}^{\binom{N-2}{s-2}} V(S_{j_3, \{i^*, o\}}) - \sum_{j_3=1}^{\binom{N-2}{s-2}} V(S_{j_3, \{i^*, o\}} \setminus \{o\})$$

$\binom{N-2}{s-2}$  is the number of coalitions of size  $s$  containing both players  $i^*$  and  $o$ .  
The marginal contribution of player  $o$  in coalition  $S$  is given by:

$$V(S) - V(S \setminus \{o\}) = \frac{\sum_{k_1=1}^s v_{k_1, S}}{\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1, S_{j_2}}} - \frac{\sum_{k_2=1}^{s-1} v_{k_2, S \setminus \{o\}}}{\sum_{j_4=1}^{\binom{N}{s-1}} \sum_{k_2=1}^{s-1} v_{k_2, S_{j_4}}}$$

$$\begin{aligned} \sum_{j_3=1}^{\binom{N-2}{s-2}} V(S_{j_3, \{i^*, o\}}) - V(S_{j_3, \{i^*, o\}} \setminus \{o\}) &= \frac{\sum_{j_3=1}^{\binom{N-2}{s-2}} \sum_{k_1=1}^s v_{k_1, S_{j_3, \{i^*, o\}}}}{\sum_{j_2=1}^{\binom{N}{s}} \sum_{k_1=1}^s v_{k_1, S_{j_2}}} \\ &\quad - \frac{\sum_{j_3=1}^{\binom{N-2}{s-2}} \sum_{k_2=1}^{s-1} v_{k_2, S_{j_3, \{i^*, o\}} \setminus \{o\}}}{\sum_{j_4=1}^{\binom{N}{s-1}} \sum_{k_2=1}^{s-1} v_{k_2, S_{j_4}}} \end{aligned}$$

$$\begin{aligned} \sum_{j_3=1}^{\binom{N-2}{s-2}} V(S_{j_3, \{i^*, o\}}) - V(S_{j_3, \{i^*, o\}} \setminus \{o\}) &= \frac{\binom{N-2}{s-2} v_{i^*} + \binom{N-2}{s-2} v_o + \binom{N-3}{s-3} \sum_{\substack{k_5=1 \\ k_5 \neq i^*, o}}^N v_{k_5}}{\binom{N-1}{s-1} \sum_{k_4=1}^N v_{k_4}} \\ &\quad - \frac{\binom{N-2}{s-2} v_{i^*} + \binom{N-3}{s-3} \sum_{\substack{k_5=1 \\ k_5 \neq i^*, j}}^N v_{k_5}}{\binom{N-1}{s-2} \sum_{k_4=1}^N v_{k_4}} \end{aligned}$$

In the case of a mandatory player, any non mandatory player cannot form a coalition of less than 2 members.

$$\begin{aligned} \phi_o(v) &= \frac{1}{N!} \sum_{s=2}^N (N-s)!(s-1)! \left( \frac{\binom{N-2}{s-2} v_{i^*} + \binom{N-2}{s-2} v_o + \binom{N-3}{s-3} \sum_{\substack{k_5=1 \\ k_5 \neq i^*, o}}^N v_{k_5}}{\binom{N-1}{s-1} \sum_{k_4=1}^N v_{k_4}} \right) \\ &\quad - \frac{1}{N!} \sum_{s=2}^N (N-s)!(s-1)! \left( \frac{\binom{N-2}{s-2} v_{i^*} + \binom{N-3}{s-3} \sum_{\substack{k_5=1 \\ k_5 \neq i^*, o}}^N v_{k_5}}{\binom{N-1}{s-2} \sum_{k_4=1}^N v_{k_4}} \right) \end{aligned}$$



Hence,

$$\begin{aligned}\phi_o(v) &= \frac{1}{v_T} \left( \left( \sum_{s=2}^N \frac{\binom{N-1}{s-2} - \binom{N-1}{s-1} \binom{N-2}{s-2}}{\binom{N-1}{s-1} \binom{N-1}{s-2} s \binom{N}{s}} \right) v_{i^*} + \left( \sum_{s=2}^N \frac{\binom{N-2}{s-2}}{\binom{N-1}{s-1} s \binom{N}{s}} \right) v_o \right) \\ &\quad + \frac{1}{v_T} \left( \sum_{s=3}^N \frac{\binom{N-1}{s-2} - \binom{N-1}{s-1} \binom{N-3}{s-3}}{\binom{N-1}{s-1} \binom{N-1}{s-2} s \binom{N}{s}} \right) (v_T - v_{i^*} - v_o)\end{aligned}$$

$$\begin{aligned}\phi_o(N, \varphi_{i^*}, \varphi_o) &= \left( \sum_{s=2}^N \frac{\binom{N-1}{s-2} - \binom{N-1}{s-1} \binom{N-2}{s-2}}{\binom{N-1}{s-1} \binom{N-1}{s-2} s \binom{N}{s}} \right) \varphi_{i^*} \\ &\quad + \left( \sum_{s=2}^N \frac{\binom{N-2}{s-2}}{\binom{N-1}{s-1} s \binom{N}{s}} \right) \varphi_o + \left( \sum_{s=3}^N \frac{\binom{N-1}{s-2} - \binom{N-1}{s-1} \binom{N-3}{s-3}}{\binom{N-1}{s-1} \binom{N-1}{s-2} s \binom{N}{s}} \right) (1 - \varphi_{i^*} - \varphi_o)\end{aligned}$$

## Appendix C

# Closed-form expression for Shapley value of a player in the case with only mandatory players

Let us consider that all players are mandatory. Then, only the grand coalition can be formed, whose value is  $V(N)$ , the fixed energy consumption to impute to service categories. According to (2.13), the payoff of a player  $k$  is:

$$\phi_k = \frac{1}{N!}(N - N)!(N - 1)!$$

$s$  is always equal to  $N$  and the marginal contribution of any player in the grand coalition is the value of the grand coalition as all players are mandatory.  $V(N) - V(N \setminus \{k\}) = 1$ , since  $V(N \setminus \{k\}) = 0, \forall k$ .

As a reminder, payoffs and values are normalized by the fixed energy consumption, i.e.,  $V(N)$ .

So,

$$\phi_k(N) = \frac{1}{N}$$

Hence, the uniform sharing is a special case of the Shapley-based sharing, when all the players are mandatory.

## Appendix D

# Energy consumption of network equipment

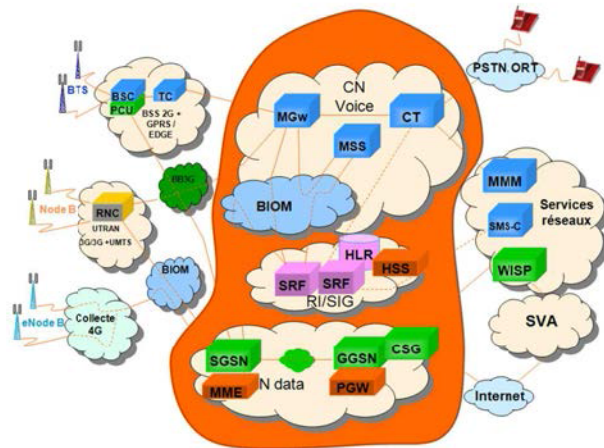


Figure D.1: Architecture of a mobile network

Values of energy and power consumption given in tables D.1, D.2, D.3, D.4, D.5 concern only the network equipment and do not take into account the technical environment (Cooling system, converters,...).

Table D.1: Energy consumption of CSCN equipment, years 2012 – 2020

Equipment	2012	2013	2014	2015	2016	2017	2018	2019	2020
MSC-Server	561	480	398	317	236	154	154	154	154
CS-MGW	1983	1983	1983	1454	925	397	397	397	397
HBSC	42	0	0	0	0	0	0	0	0
MSC interco	57	57	57	57	57	57	57	57	57

Table D.2: Power consumption of CSCN equipment, year 2012

Equipment	Theoretical power
MSC-Server APZ 212 50	2.1 kW
MSC-Server APZ 212 40	0.935 kW
MGW GMP V3.0	3.3 kW
MGW GMP V2.0	2.4 kW
ET4-1	0.435 kW

Table D.3: Energy consumption of PSCN/EPC equipment, years 2012 – 2020

Equipment	2012	2013	2014	2015	2016	2017	2018	2019	2020
SGSN	386	338	290	241	193	145	97	48	0
GGSN	108	95	81	68	54	41	27	14	0
GGSN's auxiliary equipment	1936	1694	1452	1210	968	726	484	242	0
EPC	405	487	569	651	733	815	897	979	1061
EPC's auxiliary equipment	1079	1314	1550	1785	2020	2256	2491	2726	2962

Table D.4: Power consumption of PSCN/EPC equipment, year 2012

Equipment	Theoretical power
SGSN	2.2 kW
GGSN M120	2.15 kW
GGSN J20	0.75 kW
ASR5K Cisco	405 MWh
Extra equipment related to EPC	1079 MWh

Table D.5: Access to transport equipment, years 2012 – 2020

Equipment	2012	2013	2014	2015	2016	2017	2018	2019	2020
ATM backhaul	1212	808	404	0	0	0	0	0	0
IP backhaul/backbone	3145	3373	3601	3828	3828	3828	3828	3828	3828
O&M network	1110	1110	1110	1110	1110	1110	1110	1110	1110
Gi/S Gi backbone to PDN	90	90	90	90	90	90	90	90	90
TDM backhaul/backbone	218	162	111	65	59	54	54	54	54

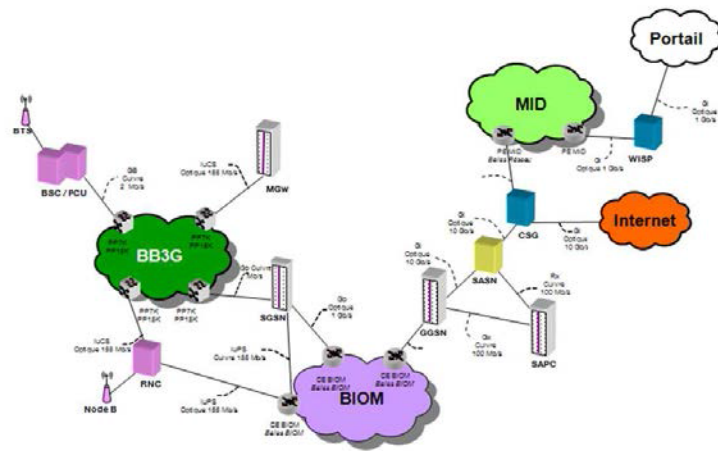


Figure D.2: Transport network for mobile data

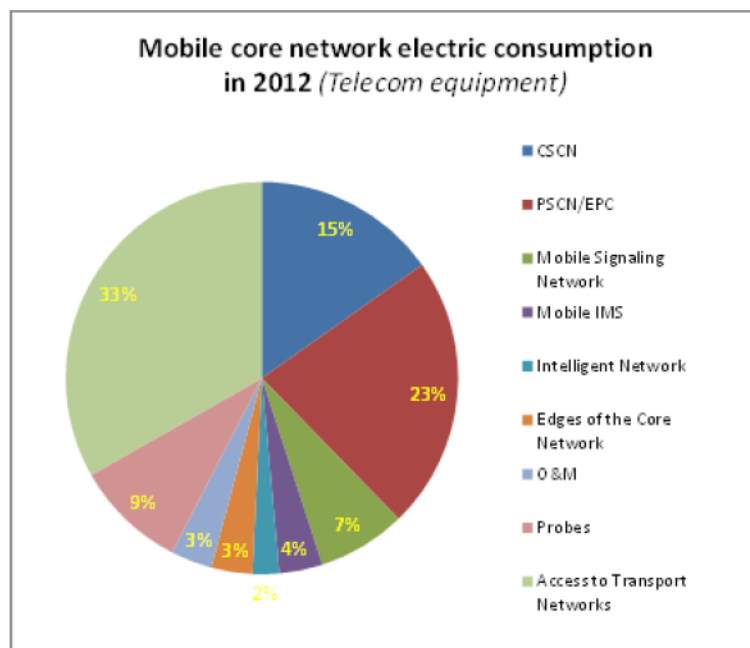


Figure D.3: Distribution of the mobile core network energy consumption, year 2012

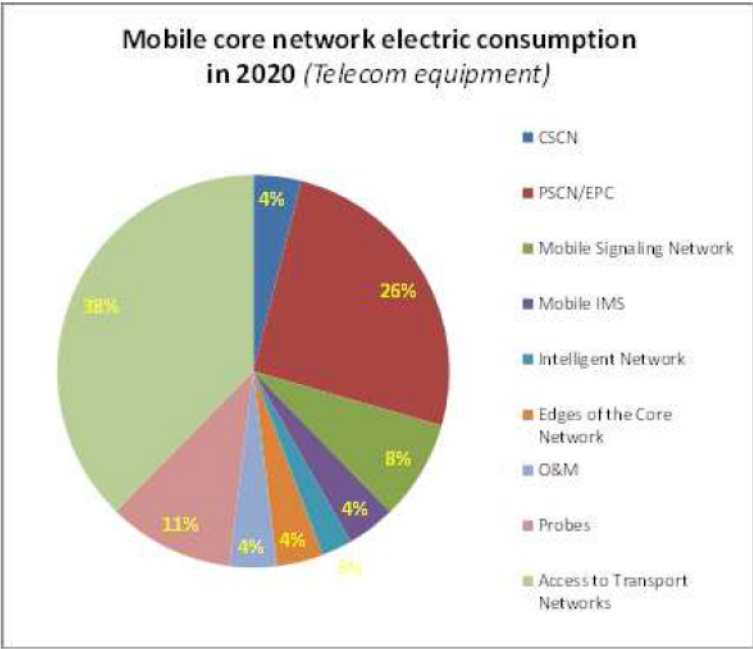


Figure D.4: Distribution of the mobile core network energy consumption, year 2020



## Appendix E

### Network's traffic

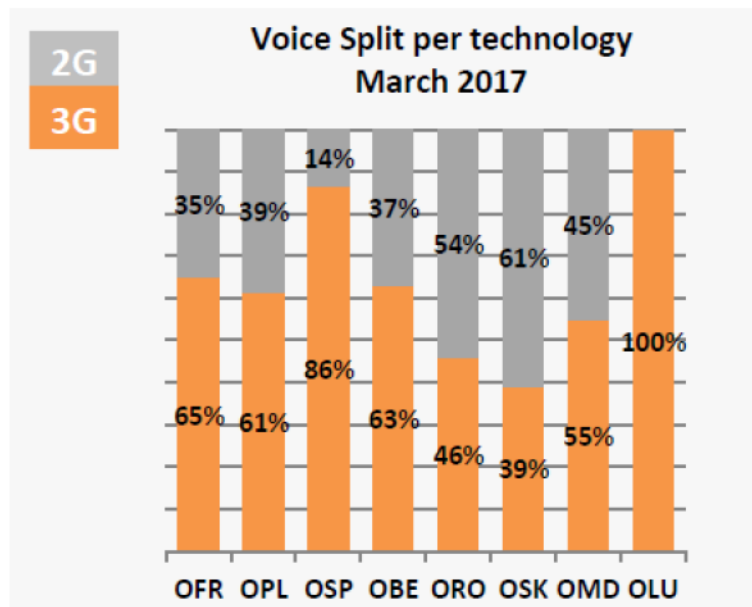


Figure E.1: Voice distribution per radio technology

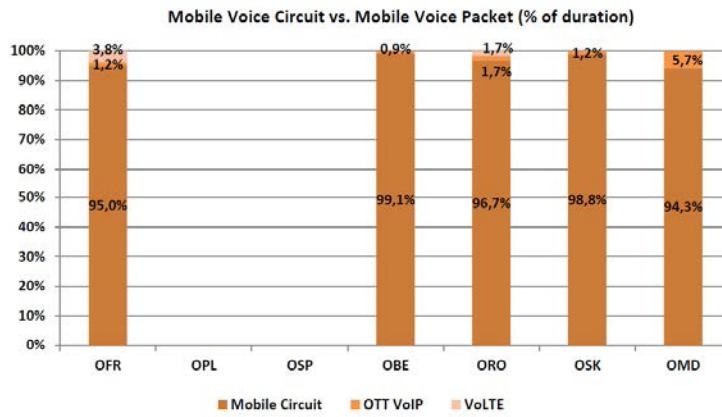


Figure E.2: Circuit Voice versus data Voice

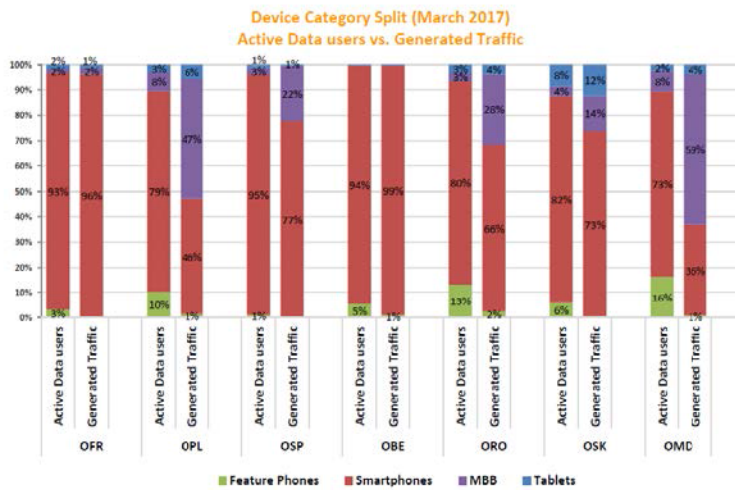


Figure E.3: Distribution of end-users' devices

**Total Traffic Split per Application category  
March 2017**

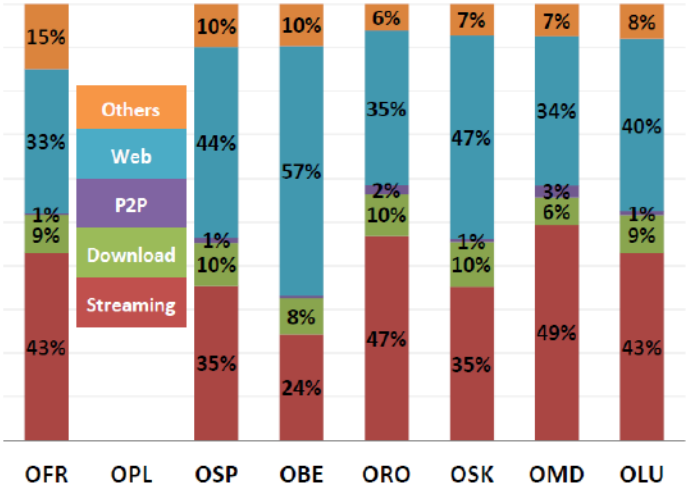


Figure E.4: Traffic distribution per service

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# List of publications

[1] W. Yoro, M. El Tabach, T. En-Najjary, A. Gati, and T. Chahed, "Sharing of energy among service categories in wireless access networks using Shapley value," in *Wireless Communications and Mobile Computing Conference (IWCMC)*, pp. 422–429, IEEE, 2016.

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