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# Service-oriented Sharing of Energy in Wireless Access Networks Using Shapley Value

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***Abstract*—We investigate in this paper the sharing of energy consumption among service categories in the access of a wireless network. We focus on the fixed component of the energy consumption, which is known to be significantly larger than the load-dependent variable component, and propose its sharing among the service categories based on coalition game concept, the Shapley value. We consider five service categories, two large players: streaming and web browsing, and three smaller ones: download, voice and other minor services, and compare our proposal with two other sharing methods: uniform and proportional which follows the same traffic proportions. Our results, applied on a real dataset extracted from an operational network in Europe, show that our proposal is more fair both towards small services in that it reduces their shares in comparison to the uniform approach and towards larger services as it reduces their shares in comparison with the proportional one. Indeed, our Shapley-based model accommodates both short term network behavior, in which the fixed energy component is independent of the traffic load, and longer term behavior, in which it varies with the load and infrastructure. Uniform sharing accounts only for the short term, and the proportional one only for the longer term.**

***Index Terms*—Energy consumption, Service-oriented, Mobile networks, Shapley value.**

## I. Introduction

According to Cisco [1], overall IP traffic will grow at a compound annual growth rate of 23 percent from 2014 to 2019. In order to face the Internet's growth, Internet providers upgrade their networks so as to keep up or improve the users perceived Quality of Experience. This leads to an increase in power consumption, resulting in turn in two main challenges: economical, as operators margin is decreasing and ecological, in a context aiming at reducing greenhouse gas emissions. Thus the research in green networking has fostered a number of investigations. For instance, Debaillie et al. [2] and Vu et al. [3] propose models for assessing the energy consumption of the mobile access network. Vu et al. [4] and Jada et al. [5] introduce models for optimizing the energy consumption of the mobile access. Bianzino et al. [6] and McLauchlan et al. [7] discuss the main trends in the fields of green networking and green energy.

If modeling the energy consumption of network elements is important for optimization sake, investigations are more and more focusing on the energy impact of services on the network. In fact, knowing the energy consumption induced by services should help in the eco-design of applications. Indeed, in order to reduce the energy consumption of the network, a promising way consists in optimizing the energy consumed by the network elements to offer a given service. To do so, one needs a model to assess the energy consumption induced by services so as to measure the energy efficiency gain related to green techniques. For example, the model can be implemented in a Life Cycle Assessment (LCA) software. A LCA software allows users to evaluate, compare and track the environmental performance of products, using notably steps suggested by ISO14040 which specifies the principles and the framework applicable to realize LCA, Ines et al. [8].

To date, the existing models assess mostly the energy consumption for some specific applications (we will report on some of them in section II). We propose in this work a model for sharing the global energy consumption of a mobile access network among the provided *services*. By "sharing", we mean the sharing of the responsibility of the energy consumption between the different service providers using the network. In effect, traffic in the network originates from different service providers, such as Google, Youtube, voice calls, etc. We group in this paper services into five categories: streaming, web, download, voice and other minor services. We call each service category a player. We propose to share the responsibility of the network's energy consumption between these players. The players' responsibility may represent their contribution in the network's carbon footprint for example.

We focus specifically on the fixed component of energy consumed in a mobile access network and its sharing between different service categories. We consider several service categories representing players of different sizes, large and small, in terms of traffic loads. We decompose the energy into variable versus fixed components and share the former in a manner that is proportional to the traffic proportion of each service category. As of the latter, we propose an approach based on coalition game concept, the Shapley value [9].

We consider two settings: one with a constant network infrastructure and one with an evolving one, over a larger time scale, in terms of additional and/or changing equipment so as to keep up with an increase in the traffic load. In the former setting, energy consumption as well as traffic load shall be considered as constant, whereas in the latter setting, they would both increase.

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

Unlike an equal sharing of the fixed energy that is unfair towards players with small traffic load, and a sharing proportional to the traffic load that puts too much weight on the players with large volume of traffic, our Shapley-based model is a trade-off for all the players in that it puts less weight on small players than equal sharing, and less weight on big players than proportional sharing. Our results encourage hence the transport of services with small traffic as well as the introduction of novel ones, and also acknowledge the role of services with large traffic as major drivers for network activity and increased deployment.

The remainder of this paper is organized as follows. In section II, we review some literature related to the assessment of energy consumption per service category. In section III, we describe our Shapley-based models for sharing the fixed component of the energy consumption among service categories. We discuss some implementation issues of the Shapley-based model and how we tackle these issues in section IV. In section V, we run numerical applications, comparing our Shapley-based proposal to uniform as well as proportional sharing of energy, on a real dataset taken from an operational European network transporting three main service categories: streaming, browsing and download, in addition to voice and other minor services. Eventually, section VI concludes the paper.

## II. Related work.

Marquet et al. [10] investigate the energy consumption of information and communication technology services and CO2 emission at life-cycle of the equipment, including 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. The model for assessing the end-to-end energy consumption of a service is based on the notion of consumption rate, i.e., the energy consumed per unit of service, for example kWh/hour/user. However, no distinction is made between fixed and dynamic energy consumption components.

Jalali et al. [11] discuss an energy model in order to estimate the energy consumption of cloud applications, and is applied to the case of sharing photos on Facebook. The model consists in determining the energy consumed per bit on a device, then multiplied by the traffic volume of the service. Only the load dependent power component is considered, the fixed power component is ignored since it is independent of services.

Preist et al. [12] provide a statistical model to calculate the overall energy output required for a digital service, from a Datacenter to the end user, using Monte Carlo analysis. No information is given about the nature of the energy consumption, fixed, dynamic or both.

To date, the investigations in the literature related to modeling the energy consumption of services are based on inputs that are very difficult or even impossible to measure. Marquet et al. [10] and Jalali et al. [11] cited above base their model on the energy consumed per transmitted bit of the service by the equipment implied on the path of the service flow. This approach has several limits. Firstly, it allows modeling much more the energy consumed by an application than the one consumed by a service. Secondly, it is quite impossible to measure the energy consumed per bit of service, as most of the time network equipment serve several services simultaneously. In order to overcome this complexity, the authors mostly refer to the power consumption models of the constructors which do not reflect the reality of the field. We propose to base our model on realistic inputs, i.e., the traffic volumes or proportions of the service categories.

Depending on which network segment is considered, one of these component is preponderant over the other. For example, the energy consumption in the core of the network is largely load-dependent because routers energy consumption varies significantly with utilization, while it is largely independent of the load in the RAN because the access is typically underloaded (typically $\rho < 50\%$ so as not to exceed some operating load threshold). Fig. 1 shows the power consumption of an operating 4G base station versus its traffic load. These values come from traffic and power measurement probes installed in Orange France's network. At $10\%$ of load, the fixed power consumption represents $91\%$ of the base station total power consumption.

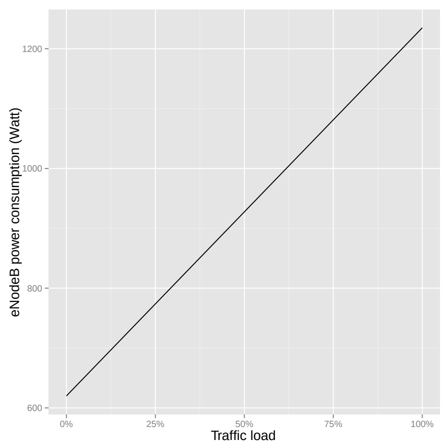


Fig. 1. Power consumption of a 4G base station.

## III. Modeling of the energy consumption sharing.

### A. Description of the system.

A wireless network is composed mainly of three segments, the access, the transport and the core, [13], [14], running possibly several technologies: 2G, 3G and 4G, as shown in Fig. 2.

The Radio Access Network is the segment of the mobile network interfacing the end-users and the mobile core network. The GSM EDGE Radio Access Network is composed of the Base Transceiver Station (BTS) and the Base Station Controller (BSC). A BTS implements minimum shift keying modulation for GSM and phase shift keying modulation for EDGE. It provides essentially voice services. The controller is in charge of the radio resource management and implements

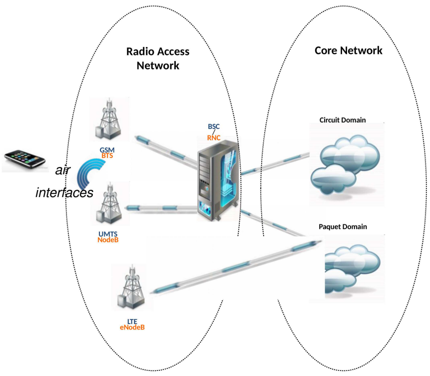


Fig. 2. The system.

resource allocation algorithms. A BSC implements Time Division Multiple Access which consists in dividing the radio resource into $8$ time slots allocated to users.

The UMTS Terrestrial Radio Access Network is composed of the NodeB and the Radio Network Controller (RNC). The NodeB implements hyper phase shift keying modulation and provides voice and data services. The RNC, as with GSM, is in charge of the management of the radio resource and implements Wideband Code Division Multiple Access as resource allocation algorithm.

The eNodeB hosts both the base station and the controller functions in a single equipment, for LTE networks. Orthogonal Frequency Division Multiplex is the modulation technology and Orthogonal Frequency Division Multiple Access the resource allocation algorithm. LTE provides data services only.

Alongside with the network elements on a site, there are the equipment of the Technical Environment composed of the cooling system, the rectifiers and the backup battery.

Traffic and energy measurements are regularly made on the network for management and investigation purposes. These measures will feed our models in the numerical applications.

### B. Energy consumption model

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 $E$ to be shared among the provided service categories. As stated earlier, the energy consumed by the access equipment is composed of a variable and a fixed components, denoted by $E^v$ and $E^f$, respectively. Then we have

$$E = E^v + E^f \tag{1}$$

Denoting by $E_i$ the energy consumption induced by service category $i$, with variable and fixed components $E_i^v$ and $E_i^f$, respectively,

$$E_i = E_i^v + E_i^f \tag{2}$$

We first focus on the variable component of the energy consumption of service category $i$. Let us denote by $v_i$ the traffic volume of service category $i$.

$$E_i^v = \varphi_i \times E^v \tag{3}$$

where $\varphi_i$ is the share of service category $i$ in $E^v$, given by :

$$\varphi_i = \frac{v_i}{\sum_{k=1}^{N} v_k} \tag{4}$$

As of the fixed energy component :

$$E_i^f = \phi_i \times E^f \tag{5}$$

where $\phi_i$ is the share of service category $i$ in $E^f$.

Unlike the variable component of the energy consumption, that is, as shown above, proportional to the traffic proportions, we propose in this work to determine $\phi_i$ using the Shapley value.

We begin by giving some introductory material on the Shapley value concept, [9], [15]. This mathematical tool has a number of applications in telecommunications, [16]–[18].

### C. Shapley value

#### 1) Cooperative game theory

: 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). These are opposed to non-cooperative games in which there is no possibility to forge alliances. 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 equilibriums.

In cooperative game theory, there are two types of solution concepts. The unobjectionable solutions and the equitable solutions. The former guarantees 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. Such solutions include the core. The core is the set of imputations under which no coalition has a value greater than the sum of its members' payoffs. Therefore, no coalition has incentive to leave the grand coalition and receive a larger payoff. An imputation is a solution of the cooperative game 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. A solution is a vector of $\mathcal{R}^N$ that represents the allocation to each player, with $N$ the number of player. Equitable solutions take into account some consideration of equity between players. Such solutions include the Shapley value. In this paper, we are considering the sharing of the responsibility of the network's energy consumption between the players in a fair way, and hence the use of the Shapley value concept.

*2) Shapley value definition and properties*
*:* The Shapley value is a cooperative game concept used for sharing a common gain between the members of a coalition, in a fair way. The fairness of the Shapley value comes from the fact that the payoff of each player in the common gain is proportional to its contribution in the coalition's gain. Let us consider a game $\xi(N,V)$ with $N$ denoting the number of players and $V$ the characteristic function associating to each coalition of the game a value. A coalition is a set of players that cooperate so as to improve their revenue. The grand coalition consists of all the players. There are $N!$ possible scenarios of constructing the grand coalition.

Let $S_i^\sigma$ denote the largest coalition not containing yet player $i$ in the construction of the grand coalition with regard to scenario $\sigma$. We define the incremental cost vector associated to the scenario $\sigma$ by:

$$c_{inc}^{\sigma} = (c_{inc}^{\sigma}(\{1\}), \cdots, c_{inc}^{\sigma}(\{i\}), \cdots, c_{inc}^{\sigma}(\{N\})) \quad (6)$$

where $c_{inc}^{\sigma}(\{i\}) = V(S_i^\sigma \cup \{i\}) - V(S_i^\sigma)$, i.e., the marginal contribution of player i in $V(S_i^\sigma \cup \{i\})$.

The Shapley value $x_{Shapley}$ is the arithmetic mean of the incremental cost vectors associated to the scenarios of constructing the grand coalition,

$$x_{Shapley} = \frac{1}{N!}\sum_{\sigma} c_{inc}^{\sigma} \quad (7)$$

The Shapley value derived from the following axioms ($\phi_i$ is the payoff of player $i$) :

- **Efficiency Axiom:** $\sum_{i\in\mathcal{N}} \phi_i(V) = V(\mathcal{N})$
- **Symmetry Axiom:** If player $i$ and player $j$ are such that $V(S\cup\{i\}) = V(S\cup\{j\})$ for every coalition S not containing player $i$ and player $j$, then $\phi_i(V) = \phi_j(V)$.
- **Dummy Axiom:** If player $i$ is such that $V(S) = V(S\cup\{i\})$ for every coalition $S$ not containing $i$, then $\phi_i(V) = 0$.
- **Additivity Axiom:** If $u$ and $v$ are characteristic functions, then $\phi(u+v) = \phi(v+u) = \phi(u) + \phi(v)$.

### D. Game without mandatory players

As stated earlier, the game is characterized by $\xi(N,V)$, with $N$ the number of players and $V$ the characteristic function. The characteristic function allocates to each coalition a cost, corresponding to a fraction of the fixed energy consumption.

Let $S$ denote a coalition of size $s$, with $s = |S|$, $|.|$ the cardinal function. In the sequel, the payoffs of the players and values of the coalitions are normalized by the fixed energy consumption of the network, unless otherwise stated.

$$V(S) = \frac{\sum_{k_1=1}^{s} v_{k_1,S}}{\sum_{j_2=1}^{C_N^s}\sum_{k_1=1}^{s} v_{k_1,S_{j_2}}} \quad (8)$$

The value of coalition $S$ is the ratio of its traffic volume versus the traffic volume of all the coalitions of same size as $S$, whose number is $C_N^s$. $v_{k,S}$ is the traffic volume of the $k^{th}$ player of coalition $S$.

The intuition behind the characteristic function can be seen as follows: the value of a coalition should be a function of the traffic volume and the number of services, as the fixed energy can be shared equally among the players when considering it is constant, or shared proportionally to the traffic volumes when considering it is load-dependent. Then, when considering only coalitions having the same number of members, we fix the variable related to the number of services, and so the value of a coalition should be only proportional to its traffic volume. Thus, the value of a coalition is the ratio of its traffic volume versus the traffic volume of the coalitions having the same number of members as the given coalition. This explains the characteristic function we defined.

Now that the characteristic function of the game is determined, we use the Shapley value concept to compute the payoffs of the players. According to Shapley, the payoff $\phi_i$ of player $i$ is:

$$\phi_i(V,S) = \frac{1}{N!}\sum_{s=1}^{N}(N-s)!(s-1)!\sum_{j_1=1}^{C_{N-1}^{s-1}}\delta(\{i\},S) \quad (9)$$

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 the coalition $S$ with the entry of player $i$.

The computational complexity of (9) grows exponentially in the number of service categories, which could represent an obstacle for being implemented. We hence propose a closed-form expression for the Shapley value computation, derived from (9).

Let $p_i$ denote the traffic proportion of player $i$: $p_i = \frac{v_i}{v_t}$.
The Shapley value of $i$ is then:

$$\phi_i(N,p_i) = (\sum_{s=1}^{N}\frac{1}{sC_N^s})p_i + (\sum_{s=2}^{N}\frac{(C_{N-1}^{s-2} - C_{N-1}^{s-1})C_{N-2}^{s-2}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})(1-p_i) \quad (10)$$

The derivation of this expression is found in Appendix A.

### E. Game with a mandatory player

Let us now consider a game with a mandatory player. As stated above, 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 given network infrastructure. A mandatory player is such that there can not exist any coalition without him.

Let us denote by $i*$ the mandatory player and $o$ a non mandatory player. The characteristic function of the game is defined as follows:

$$V(S) = \frac{\sum_{k_1=1}^{s} v_{k_1,S}}{\sum_{j_2=1}^{C_N^s}\sum_{k_1=1}^{s} v_{k_1,S_{j_2}}}\mathbf{1}_{i*\in S} \quad (11)$$

$\phi_{i*}$ and $\phi_o$ of the mandatory player $i*$ and a non mandatory player $o$, respectively, are obtained by (9).

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

$$\phi_{i*}(N,p_{i*}) = (\sum_{s=1}^{N}\frac{1}{sC_N^s})p_{i*} + (\sum_{s=2}^{N}\frac{C_{N-2}^{s-2}}{C_{N-1}^{s-1}sC_N^s})(1-p_{i*}) \tag{12}$$

The derivation of this expression is found in Appendix B-A.

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

$$\begin{aligned}\phi_o(N,p_{i*},p_o) = &(\sum_{s=2}^{N}\frac{(C_{N-1}^{s-2}-C_{N-1}^{s-1})C_{N-2}^{s-2}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})p_{i*}\\ &+(\sum_{s=2}^{N}\frac{C_{N-2}^{s-2}}{C_{N-1}^{s-1}sC_N^s})p_o\\ &+(\sum_{s=3}^{N}\frac{(C_{N-1}^{s-2}-C_{N-1}^{s-1})C_{N-3}^{s-3}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})(1-p_{i*}-p_o)\end{aligned} \tag{13}$$

The derivation of this expression is found in Appendix B-B.

### F. Game with only mandatory players

Let consider a game where all players are mandatory. The closed-form Shapley value of a player is given by:

$$\phi_k(N) = \frac{1}{N} \tag{14}$$

The derivation of this expression is found in Appendix C.

Thus, in the special case where all the players are mandatory, the fixed energy consumption is uniformly distributed among the service categories, whatever the traffic volume proportions. The uniform model is a special case of the Shapley-based model.

It is worth to note that the closed-form equations are simplification of the Shapley value equation, reducing significantly the computational complexity of the algorithm, but we lose at the same time the generality of the Shapley value equation. Indeed, since the closed-form equations come from the replacement of the characteristic function $V$ in the Shapley equation (Eqn. (9)) by its analytical expressions we defined in our work, these equations are therefore specific to the game we investigate.

### G. Heterogeneous radio access network model

When the network is composed of several access technologies, the sharing of the energy consumption is done per radio technology, then we deduce the overall sharing considering all the technologies.

Let $\mathcal{T}$ denote the set of radio technologies, $\mathcal{F}_t$ the set of services served by the sub-network associated with radio technology $t$, $E_t^v$ ($E_t^f$) the variable (fixed) energy consumption of the sub-network $t$, $v_{i,t}$ the traffic volume of service category $i$ on sub-network $t$. The total network energy consumption (variable and fixed) induced by the service $i$ is :

$$E_i = \sum_{t\in\mathcal{T}}(\frac{v_{i,t}}{\sum_{k\in\mathcal{F}_t}v_{k,t}}\ E_t^v + \phi_{i,t}\ E_t^f) \tag{15}$$

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

$$E_i = \sum_{t\in\mathcal{T}}(\theta_t\ \frac{v_{i,t}}{\sum_{k\in\mathcal{F}_t}v_{k,t}} + (1-\theta_t)\ \phi_{i,t})\ E_t \tag{16}$$

### H. Case of 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 traffic load increase, as depicted in Fig. 3.

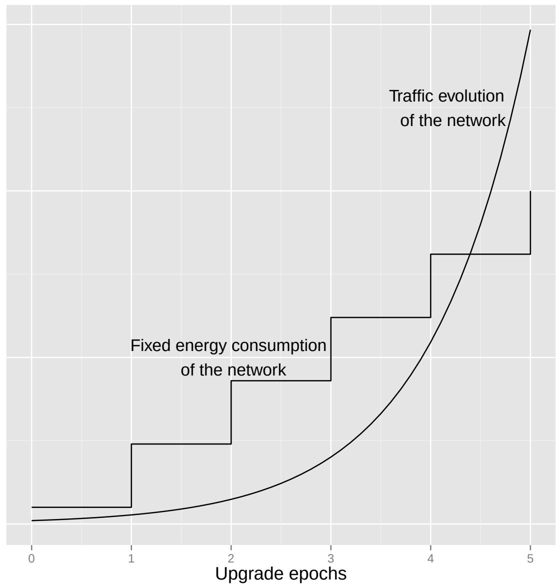


Fig. 3. Evolution of the traffic load and network infrastructure.

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

$$E_i = \sum_{l\in\mathcal{L}}\sum_{t\in\mathcal{T}}(\frac{v_{i,t,l}}{\sum_{k\in\mathcal{F}_t}v_{k,t,l}}\ E_{t,l}^v + \phi_{i,t,l}\ E_{t,l}^f) \tag{17}$$

The traffic variations impact strongly the network upgrade, and so one needs to make again a fair sharing of energy and equipment costs, that take 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.

$$E_i = \sum_{l\in\mathcal{L}}\sum_{t\in\mathcal{T}}(\frac{\delta v_{i,t,l}}{\sum_{k\in\mathcal{F}_t}\delta v_{k,t,l}}\ E_{t,l}^v + \phi_{i,t,l}\ E_{t,l}^f) \tag{18}$$

## IV. Implementation issues

Fig. 4 shows the runtime (in second) of two algorithms for the computation of the Shapley values of the service categories, one using (9) - denoted by Classical - and the other using the closed-form expression (10) - denoted by Optimized.

The algorithm using the closed-form expression (10) 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 (9) has a computational complexity growing exponentially in

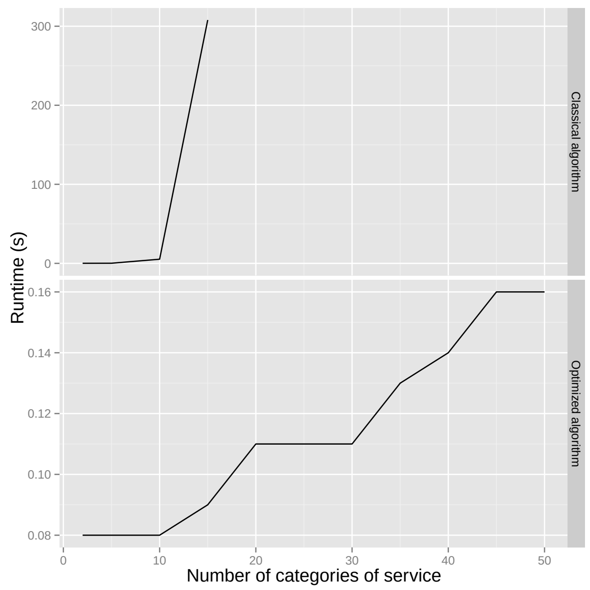


Fig. 4. Runtimes of the classical-based and closed-form-based Shapley value algorithms.

the number of service categories, does not converge and has some resource limitation from a certain number of service categories (depending on the hardware and software environment). This comes from that (9) computes the marginal contribution of each service category in all $N!$ scenarios of constructing the grand coalition, whilst the closed-form expressions we derive from (9) are simple linear functions of the traffic proportions, which can be written in the following general forms:

$$\phi_i(N, p_i) = A(N)p_i + B(N) \tag{19}$$

for (10),

$$\phi_{i*}(N, p_{i*}) = C(N)p_{i*} + D(N) \tag{20}$$

for (12) and

$$\phi_o(N, p_{i*}, p_o) = E(N)p_{i*} + F(N)p_o + G(N) \tag{21}$$

for (13), where $A(N), C(N), E(N)$, $F(N)$ represent the impact of traffic proportions in the sharing of the fixed energy consumption, and $B(N), D(N), G(N)$, the lower bounds of the players' share in the fixed energy consumption.

For example, for $N = 5$, $\phi_i(p_i) = A(5)p_i + B(5) = 0.417\ p_i + 0.117$. As depicted in Figs. 5 and 6, $A(N), B(N), C(N), D(N), G(N)$ are asymptotically equivalent to $1/N$. $E(N), F(N)$ tend faster to 0. That is (10),(12) and (13) become respectively $\phi_i(N, p_i) = \frac{1+p_i}{N}$, $\phi_{i*}(N, p_{i*}) = \frac{1+p_{i*}}{N}$ and $\phi_o(N) = \frac{1}{N}$ for large number of services.

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

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

Fig. 6 shows that the lower bound of the share of a service category depends on the number of categories defined in the model. Considering again the scenario without a mandatory player, the minimum share of a player is maximal when considering 5 service categories ($12\%$) and minimal with 2 service categories ($0\%$).

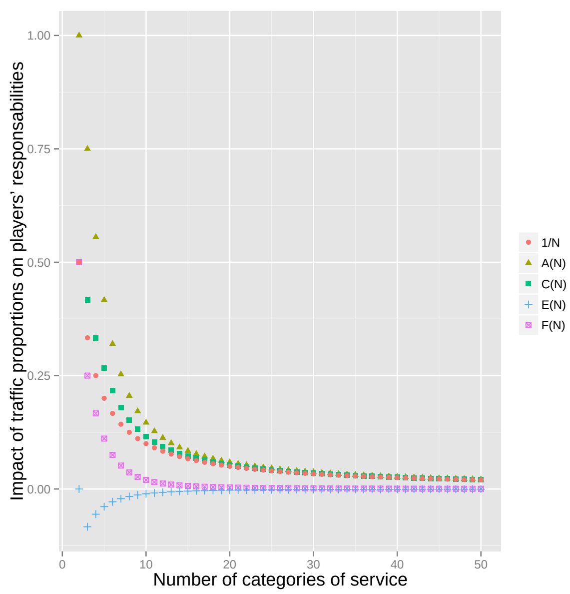


Fig. 5. Impact of traffic proportions in the fixed energy sharing.

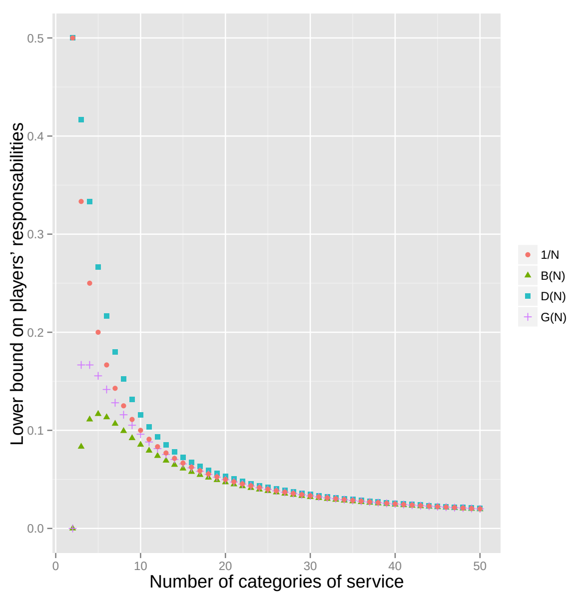


Fig. 6. Lower bounds of the players' share in the fixed energy consumption.

## V. Numerical Applications

We now turn to the evaluation of our Shapley-based sharing model of energy between different service categories. We consider Orange France's 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 segmentation for the service categories: two large ones, namely streaming and web browsing, and three smaller ones: download, voice and other minor services. Fig. 7 shows their traffic proportions as taken from the real dataset. We consider just the traffic and energy consumption of the 3G sub-network (the network of NodeBs and RNCs).

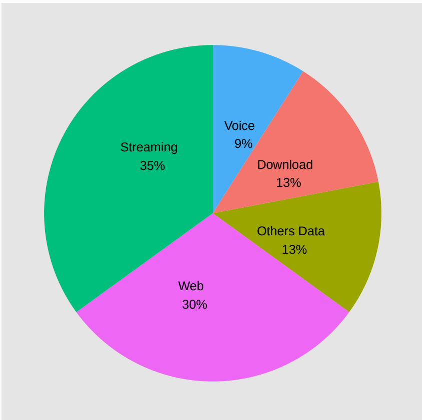


Fig. 7. Traffic proportions per service category.

The variable component of the energy consumption is shared proportionally to the traffic loads, as this component is load-dependent. This implies that data services induced $90\%$ of the UMTS Terrestrial Radio Access Network (UTRAN) variable energy consumption. These services are dominated by Over The Top (OTT) actors like Google.

### A. Performance metric

In order to quantify the comparative performance between the three sharing strategies, i.e., Shapley-based, uniform and proportional, we develop next several metrics and show that the third one will be the one we will use in our performance evaluation.

Let $\mathcal{S}$ denote the set of strategies of the players. $\mathcal{S} = \{u, p, s\}$ with $u$ denoting the uniform model, $p$ the proportional model, and $s$ the Shapley-based model. Each player has three strategies he can play. Let $\mathcal{N}$ denote the set of players, $x_i^k$ the fixed energy share of player $i$ when playing strategy $k$. Let $\tilde{x}_i$ denote the minimum share of player $i$, with regard to its strategies.

$$\tilde{x}_i = min((x_i^k)_{k \in \mathcal{S}}) \tag{22}$$

$\tilde{x} = (\tilde{x}_i)_{i \in \mathcal{N}}$ is the vector of minimum shares of the players. Let $r_i^k$ denote the regret of player $i$, playing strategy $k$. It is the difference between its share when playing strategy $k$ and its minimum share.

$$r_i^k = x_i^k - \tilde{x}_i \tag{23}$$

$r_k = (r_i^k)_{i \in \mathcal{N}}$ is the regret vector of the players when strategy $k$ is chosen.

*1) Pareto-dominant strategy:* A strategy $k$ maximizes the satisfaction of the players if it is Pareto-dominant, that is, the associated regret vector, $r_k$, is such that:

$$r_i^k \leq r_i^{k\prime} \; \forall \; i \; \in \; \mathcal{N} \; , \; \forall \; k\prime \; \in \; \mathcal{S} \tag{24}$$

and

$$\exists \; i \; .s.t \; r_i^k < r_i^{k\prime} \tag{25}$$

We show that no strategy among the three we consider is Pareto-dominant. Let assume that such a strategy exists. Let $k$ and $k\prime$ be two given strategies. $k$ is a Pareto dominant strategy implies that $\sum_{i=1}^N x_i^k < \sum_{i=1}^N x_i^{k\prime} \implies 1 < 1$. This absurd result shows the non existence of a Pareto dominant strategy in this game. We thus turn to the social welfare strategy, which minimizes the mean regret of the players.

*2) Social welfare strategy:* A strategy $k$ maximizes the satisfaction of the players if it minimizes their mean regret with regard to the others strategies. However, all the strategies offer the same mean regret to the players, as shown next. Let $R_k$ denote the cumulative regret of the players, given strategy $k$.

$$\begin{aligned} R_k &= \textstyle\sum_{i=1}^N r_i^k \\ R_k &= \textstyle\sum_{i=1}^N x_i^k - \tilde{x}_i \\ R_k &= \textstyle\sum_{i=1}^N x_i^k - \sum_{i=1}^N \tilde{x}_i \\ R_k &= 1 - \textstyle\sum_{i=1}^N \tilde{x}_i \end{aligned}$$

$R_k = 1 - \sum_{i=1}^N \tilde{x}_i$ shows the cumulative regret of the players is independent of the strategy, then all the strategies have the same mean regret, hence the need to look for another order relation on $\mathcal{S}$.

*3) The strategy of the minimum variance:* A strategy $k$ maximizes the satisfaction of the players if it minimizes the variance of the associated regret vector, $r_k$, with regard to the other strategies. By minimizing the variance of the regrets, the strategy $k$ minimizes the difference between the regrets of satisfied and those of unsatisfied players. A player is satisfied when its regret is lower than the mean regret of the players, and is unsatisfied otherwise.

$$var(r_k) = min((var(r_{k\prime}))_{k\prime \in \mathcal{S}}) \tag{26}$$

The idea of the "satisfaction function of the minimum variance" is as follows: Every player has a preferred sharing model, which corresponds to the model that assigns him its lowest responsibility in the fixed energy consumption. When implementing a sharing model, a player has a regret corresponding to the difference between its responsibility given the implemented sharing approach and its lowest responsibility. Given that all the players have the same mean regret whatever the sharing model, their aim is then to minimize the differences between their regrets, hence the minimization of the variance of their regrets. The sharing model that minimizes the variance of their regrets, maximizes their satisfaction.

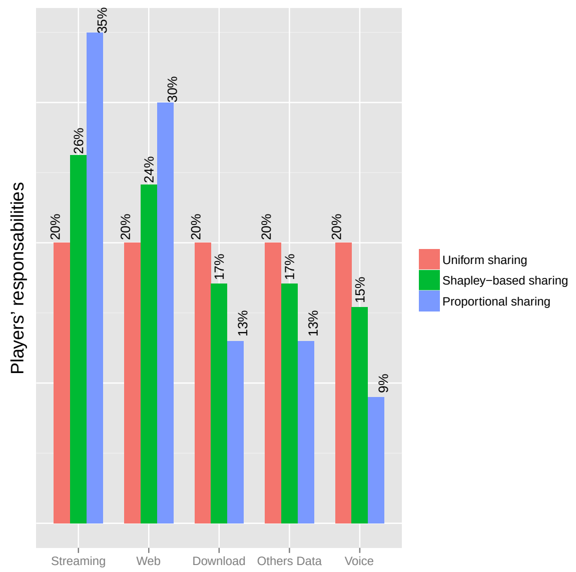


Fig. 8. Sharing of the fixed energy using three approaches: uniform, proportional and Shapley.

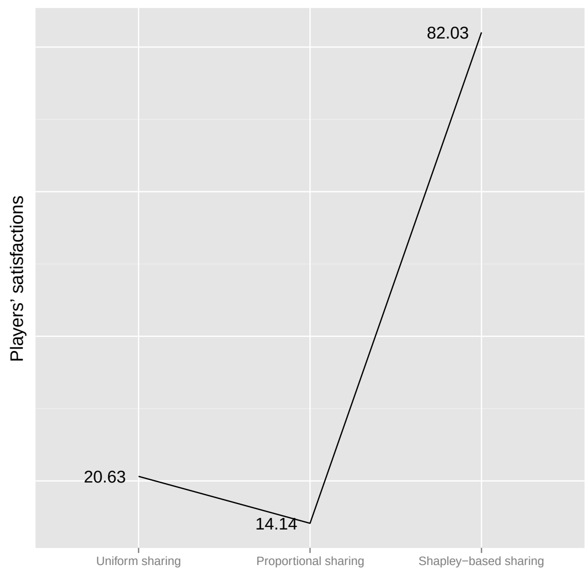


Fig. 9. Players' satisfactions per sharing approaches.

### *B. Energy sharing without a mandatory service category*

We now turn to the fixed component of the energy consumption and show in Fig. 8 the sharing achieved by our Shapley-based proposal along with two other approaches: uniform sharing between the different service categories, independently of their traffic loads as on the short term the fixed energy consumption is independent of the network traffic load. And a proportional sharing which follows the traffic proportions of the service categories, given that traffic increase over a larger time scale causes network upgrades that in turn augment the fixed energy consumption.

It is worth to notice in the figure that the uniform approach favors ”big services” (in terms of load) while ”small ones” are favored by the proportional sharing. Our Shapley-based model achieves actually a trade-off among all the players, taking into consideration the double behavior of the fixed energy as it varies or not with the traffic load according to the time scale, unlike the uniform sharing that accounts only for the short term, and the proportional approach for the longer term. Indeed ”big players”, namely streaming and web services, have a lower impact in the network fixed energy consumption than they would have had with a proportional approach, as well as ”small players”, namely voice, download and other minor services with regard to a uniform sharing.

This is a good trade-off for streaming and web services as it does not penalize them a lot and acknowledges the fact that they are major drivers for network activity, and is also a good trade-off for services with small loads as it does not make them too much responsible of the fixed energy consumption and encourages their transport as well as introduction of yet new, small ones.

The trade-off offers by our Shapley-based model to all the players results in the maximization of their satisfaction for this sharing model, as illustrated in Fig. 9. Maximizing the satisfaction is equivalent to reducing the differences between the highest and the lowest regrets of the players.

Based on our Shapley-based model, data services represent $85\%$ of the UTRAN fixed energy consumption, versus $15\%$ for voice service. We deduce that data services represent $0.91\theta_{3G} + 0.85(1 - \theta_{3G})$ of the total energy consumption (fixed and variable) of the 3G RAN. Typically $\theta_{3G} = 0.2$ because the access is under-loaded (say $\rho = 25\%$), finally data services represent $86\%$ of the total RAN energy consumption. We consider the power consumption model of the base station in Fig. 1, i.e., $P(\rho) = 0.62(1+\rho)$. For $\rho = 25\%$, $\theta_{3G} = \frac{0.775-0.62}{0.775} = 0.2$.

### *C. Energy sharing with a mandatory service category: voice*

We now turn to the case where the voice service is mandatory due to legal constraints. In this scenario, voice is not considered in the selection of the best sharing approach since it is a mandatory player, then must play whatever the sharing model.

Based on Fig. 10, the best sharing model can not be the proportional approach as the regret of big services is very high. Uniform sharing is also eliminated because it induced higher regrets for all the players with regard to the Shapley-based model. The Shapley-based sharing appears as the strategy that minimizes the difference between the players regrets, and thus maximizing their satisfaction, as depicted in Fig. 11.

It is worth to notice that the Shapley-based model takes into account the mandatory nature of the voice service by augmenting significantly its share in the fixed energy consumption (from $15\%$ to $29\%$). This results in a significant reduction of the impact of data services on the total energy consumption of the network. Data services represent now $57\%$ of the total energy consumption, that corresponds to a decrease of $29\%$ compared to the scenario where voice is not a mandatory player.

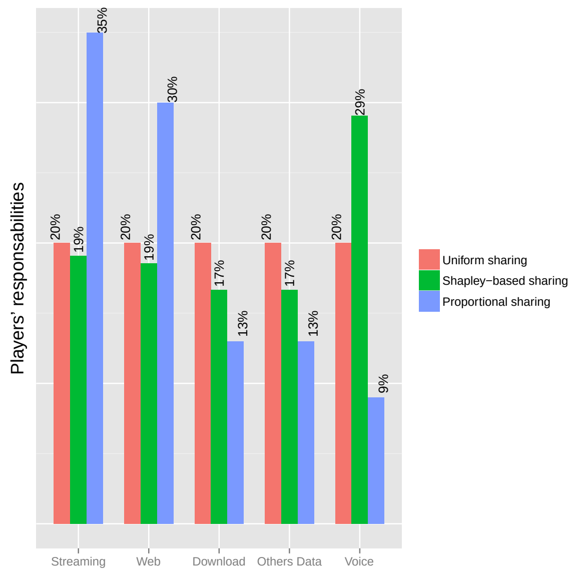


Fig. 10. Sharing of the fixed energy - voice a mandatory player.

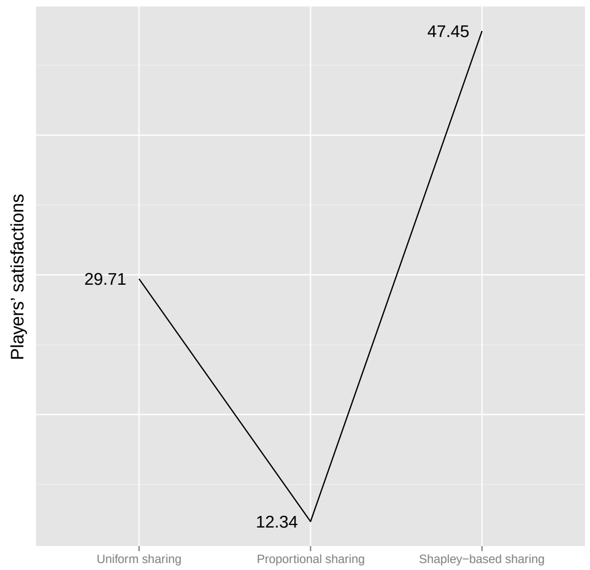


Fig. 11. Players' satisfactions per sharing approaches - voice a mandatory player.

It is a good outcome that the responsibility of the mandatory player, voice service in this work, in the network's fixed energy consumption significantly increases because the operator would be mandated by the government to implement and offer it on a national basis. And so, to offer this service, the operator would need to deploy a network and dimension it in such a way so as to reach all the citizens of the given country. In this case, the network can be seen as initially deployed to transport primarily this service, and so it is natural that it would share a large part of the responsibility of the energy consumption (yet not all of it since it is sharing the infrastructure with subsequent services).

### D. *Case of evolving network infrastructure*

We now study the case where the network infrastructure is upgraded due to a traffic increase. Fig. 12 shows real measurements for the traffic volumes 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 only the $3G$ traffic and 2 upgrade levels.

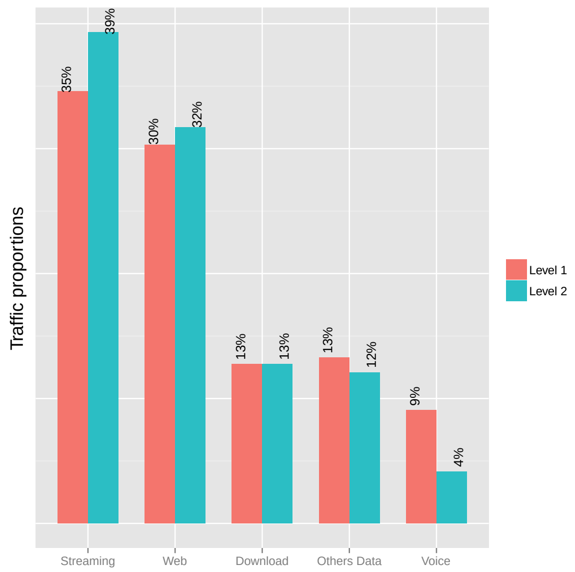


Fig. 12. Traffic per service category - case of evolving network infrastructure.

The sharing of the variable component of the energy consumption follows here too the traffic proportions, and so the corresponding figure is omitted. For the fixed component however, Fig. 13 shows the new sharing based on (10), at each level, considering both the traffic volumes and the variations of traffic, at level 2.

Considering the traffic volumes puts the weight on big services, while considering the traffic variations puts the weight on service categories whose traffic increases rapidly, taking into account the impact of traffic increase on the necessity of upgrading the network infrastructure (adding of new equipment in the network), that is itself responsible of an increase in the energy consumption, both fixed and variable.

Note that the traffic increase is correlated with the traffic volumes in the studied network. This results in a similar sharing (in terms of weights) of the fixed energy consumption among the services when considering either traffic volumes or traffic variations.

## VI. Conclusion

We investigated in this work the sharing of the energy consumed by a wireless access network among the provided service categories. We focused on the two energy components: small, load-dependent variable one and significantly larger fixed one (since the RAN is most of the time under-loaded with traffic load $\rho < 50\%$), load-independent over the short term but load-dependent over longer period of time (typically years). The former is to be shared among the different service

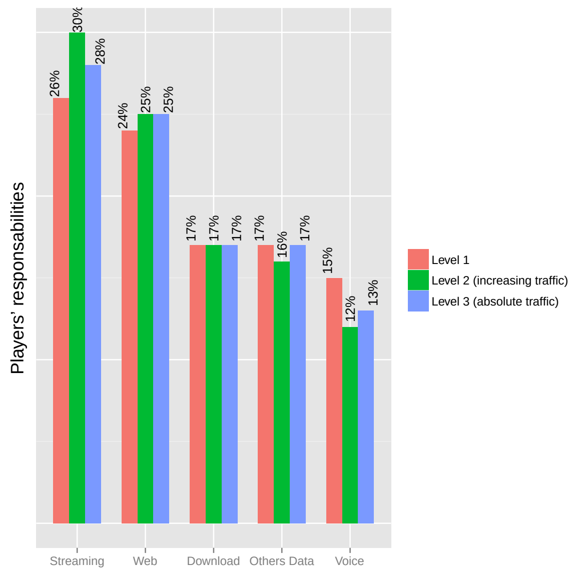


Fig. 13. Sharing of the fixed energy - case of evolving network infrastructure.

categories according to their load proportions. As of the fixed component, it can be shared in a variety of ways: the simplest one being an equal share between the players - this is unfair towards players with small traffic loads. Another one is a sharing proportional to the traffic loads - this puts too much weight on the players with large volumes of traffic, which are a major driving force for the network to be operating.

We proposed in this paper a third approach, based on the Shapley value, which put less weight on small players than equal sharing, and less weight on big players than proportional sharing. This is appreciable as it encourages transport and introduction of small services, and acknowledges the role of larger services as major drivers for network activity.

We considered two settings: one with constant network infrastructure and one with evolving network infrastructure over longer periods of time. Moreover, we considered the case of mandatory services wherein some service categories are legally obliged to be provided, such as voice service in several deployed operator networks.

Our next work will focus on the end-to-end path, from the content location in a datacenter for instance to the end user, and on the quantification as well as the sharing of the total energy consumption, again, among the different service categories in the overall network.

## Appendix A
## Closed-form Shapley value of a player in a game without mandatory players

The characteristic function of the game without a mandatory player is as follows:

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

The value of a coalition $S$ is the ratio of the traffic volume of that coalition and the traffic volume of all the coalitions having the same size as $S$, whose number is $C_N^s$, and size is $s$. $v_{k,S}$ is the traffic volume of the $k^{th}$ element of the coalition $S$.

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

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

Then,

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

$C_{N-1}^{s-1}$ is the number of coalitions of size $s$ containing player $i$, $\sum_{j_2=1}^{C_N^s} \sum_{k_1=1}^{s} v_{k_1,S_{j_2}}$ and $\sum_{j_4=1}^{C_N^{s-1}} \sum_{k_2=1}^{s-1} v_{k_2,S_{j_4}}$ 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 get them out of the sum over coalitions of same size.

$\sum_{j_1=1}^{C_{N-1}^{s-1}} \sum_{k_1=1}^{s} v_{k_1,S_{j_1,\{i\}}}$ 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 $k^{th}$ element of the $j^{th}$ coalition of size $s$ containing player $i$. Player $i$ of course is present in all the $C_{N-1}^{s-1}$ coalitions, while each other player is present in $C_{N-2}^{s-2}$ coalitions. In fact there are $C_{N-2}^{s-2}$ coalitions of size $s$ with both player $i$ and a given player $k$.

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

Then we have:

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

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

$$C_N^s = \frac{N!}{s!(N-s)!} \Longrightarrow (N-s)!(s-1)! = \frac{N!}{sC_N^s}$$

Hence,

$$\phi_i(v) = \frac{1}{v_T}(\sum_{s=1}^{N} \frac{1}{sC_N^s})v_i + \frac{1}{v_T}(\sum_{s=2}^{N} \frac{(C_{N-1}^{s-2} - C_{N-1}^{s-1})C_{N-2}^{s-2}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})(v_t - v_i)$$

Let $p_i$ denote the traffic proportion of player $i$.

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

$$\phi_i(N, p_i) = (\sum_{s=1}^{N} \frac{1}{sC_N^s})p_i + (\sum_{s=2}^{N} \frac{(C_{N-1}^{s-2} - C_{N-1}^{s-1})C_{N-2}^{s-2}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})(1 - p_i)$$

## Appendix B
## Game with a mandatory player

### A. Closed-form Shapley value of the mandatory player

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

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

The payoff of the mandatory player is :

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

In fact $V(S \backslash \{i*\}) = 0 \; \forall \; S$

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

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

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

Hence,

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

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

### B. Closed-form Shapley value of a non mandatory player

Let $o$ denote a non-mandatory player. The value of a coalition with a non mandatory player and the mandatory player is:

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

$C_{N-2}^{s-2}$ is the number of coalitions of size $s$ containing both players $i*$ and $o$.

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

$$\sum_{j_3=1}^{C_{N-2}^{s-2}} V(S_{j_3,\{i*,o\}}) - V(S_{j_3,\{i*,o\}}\backslash\{o\}) = \frac{\sum_{j_3=1}^{C_{N-2}^{s-2}}\sum_{k_1=1}^{s} v_{k_1,S_{j_3,\{i*,o\}}}}{\sum_{j_2=1}^{C_N^s}\sum_{k_1=1}^{s} v_{k_1,S_{j_2}}} - \frac{\sum_{j_3=1}^{C_{N-2}^{s-2}}\sum_{k_2=1}^{s-1} v_{k_2,S_{j_3,\{i*,o\}}\backslash\{o\}}}{\sum_{j_4=1}^{C_N^{s-1}}\sum_{k_2=1}^{s-1} v_{k_2,S_{j_4}}}$$

$$\sum_{j_3=1}^{C_{N-2}^{s-2}} V(S_{j_3,\{i*,o\}}) - V(S_{j_3,\{i*,o\}}\backslash\{o\}) = \frac{C_{N-2}^{s-2}v_i* + C_{N-2}^{s-2}v_o + C_{N-3}^{s-3}\sum_{\substack{k_5=1\\k_5\neq i*,o}}^{N} v_{k_5}}{C_{N-1}^{s-1}\sum_{k_4=1}^{N} v_{k_4}} - \frac{C_{N-2}^{s-2}v_i* + C_{N-3}^{s-3}\sum_{\substack{k_5=1\\k_5\neq i*,j}}^{N} v_{k_5}}{C_{N-1}^{s-2}\sum_{k_4=1}^{N} v_{k_4}}$$

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

$$\phi_o(v) = \frac{1}{N!}\sum_{s=2}^{N}(N-s)!(s-1)!\frac{C_{N-2}^{s-2}v_i* + C_{N-2}^{s-2}v_o + C_{N-3}^{s-3}\sum_{\substack{k_5=1\\k_5\neq i*,o}}^{N} v_{k_5}}{C_{N-1}^{s-1}\sum_{k_4=1}^{N} v_{k_4}} - \frac{1}{N!}\sum_{s=2}^{N}(N-s)!(s-1)!\frac{C_{N-2}^{s-2}v_i* + C_{N-3}^{s-3}\sum_{\substack{k_5=1\\k_5\neq i*,o}}^{N} v_{k_5}}{C_{N-1}^{s-2}\sum_{k_4=1}^{N} v_{k_4}}$$

Hence,

$$\phi_o(v) = \frac{1}{v_T}(\sum_{s=2}^{N} \frac{(C_{N-1}^{s-2} - C_{N-1}^{s-1})C_{N-2}^{s-2}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})v_i* + \frac{1}{v_T}(\sum_{s=2}^{N} \frac{C_{N-2}^{s-2}}{C_{N-1}^{s-1}sC_N^s})v_o + \frac{1}{v_T}(\sum_{s=3}^{N} \frac{(C_{N-1}^{s-2} - C_{N-1}^{s-1})C_{N-3}^{s-3}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})(v_T - v_i * - v_o)$$

$$\phi_o(N, p_i*, p_o) = (\sum_{s=2}^{N} \frac{(C_{N-1}^{s-2} - C_{N-1}^{s-1})C_{N-2}^{s-2}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})p_i* + (\sum_{s=2}^{N} \frac{C_{N-2}^{s-2}}{C_{N-1}^{s-1}sC_N^s})p_o + (\sum_{s=3}^{N} \frac{(C_{N-1}^{s-2} - C_{N-1}^{s-1})C_{N-3}^{s-3}}{C_{N-1}^{s-1}C_{N-1}^{s-2}sC_N^s})(1 - p_i * - p_o)$$

## Appendix C
## Closed-form Shapley value of a player in a game with only mandatory players

Let us consider a game where all players are considered as mandatory. In this game, only the grand coalition can be formed, whose value is $V(N)$, the fixed energy consumption to share between services. According to (9), 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. $V(N) - V(N\backslash\{k\}) = 1$, since $V(N\backslash\{k\}) = 0, \forall k$.

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

Hence,

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

We showed that the uniform sharing is a special case of the Shapley-based sharing, when all the players of the game are mandatory. This ends the proof.

## Acknowledgment

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