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Sharing the Cost of Lunch: Energy Apportionment Policies

Ekhiotz Jon Vergara, Simin Nadjm-Tehrani and Mikael Asplund
Department of Computer and Information Science
Linköping University, Sweden
{ekhiozt.vergara,simin.nadjm-tehrani,mikael.asplund}@liu.se

ABSTRACT

Energy consumption has become a hot topic in computer and communication technologies pinpointing the need to carefully analyse system efficiency. The energy consumption of a system is determined by the usage patterns of system components and complex interactions between the coexisting entities and resources. Providing transparency of a system's consumption by breaking down the total consumption is vital to evaluate and provide energy-efficient design and operation.

In this paper we survey the apportionment problem in different fields such as computer systems, wireless sensor networks, mobile devices and energy-efficient buildings. The challenge lies in how to attribute a share of the total energy consumption to the responsible entities (e.g., applications, processes or users of the system). Our analysis identifies that energy apportionment is a common problem in different fields and reviews five previously applied energy apportionment policies. Also, the work identifies relevant further research.

Categories and Subject Descriptors

C.4 [Performance of Systems]: Modeling techniques

General Terms

Design, Performance, Management

Keywords

energy apportionment; energy accounting; energy management

1. INTRODUCTION

Energy consumption and its management have been clearly identified as a challenge in computing and communication system design. Energy consumption is obviously of paramount importance for battery powered devices, but energy efficiency has also become essential for plugged systems due to core drivers such as sustainability and operational expenses.

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Even though it can be argued that energy is just another resource and that common methods for resource management could in principle be employed [16], energy management poses its own challenges [23,34]. The energy consumption created by a resource usage is complex since (1) the amount of activity of an entity is often not proportional to the consumed energy, and (2) energy consumption does not generally reflect *when* the activity happened. Additionally, the coexisting accesses to shared resources (e.g., different components of the system) by the different entities in the system aggravate the problem, which results in the actual consumption not being the sum of what the entities would consume using the resource alone.

Energy accounting is the procedure of quantifying, analysing and reporting the energy consumption of different entities or activities of interest in the system. It plays an essential role to evaluate the efficiency of entities by revealing their contribution to the total consumption and it has been identified as a core element and prerequisite for efficient energy management. There is evidence supporting the fact that energy awareness can aid to conserve energy [2,19]. Unfortunately, energy accounting inherits the cost allocation or apportionment problem of accounting in general, which does not have a general single best solution [13].

Selecting an apportionment method entails a set of principles used to achieve some rational division, and thus we call these methods energy apportionment policies. These refer to the rule that prescribes the energy cost to each entity. We illustrate the apportionment problem using two instances in the context of mobile and wireless networks, but as we describe in the paper the problem arises in multiple different contexts. In the first we focus in the energy apportionment of a wireless interface.

Figure 1: Energy apportionment example for a wireless interface.

Apportionment scenario 1: Fig. 1 exemplifies a toy apportionment case showing a simplification of a wireless interface. The system is characterised by two states, active and inactive, where an entity can perform communicate (send and receive data) only in the active state. After every transmission a timeout is activated which keeps the interface consuming energy in an active state. The timeout is a power management mechanism that also serves responsiveness by avoiding the transition delay from the inactive to active state for subsequent transmissions. Many computing and communication components or systems show a similar behaviour, such as different wireless interfaces [3, 15, 18, 32], hard drives [17], Secure Digital cards [18] or even some electric appliances [21].

Fig. 1 shows the energy consumption of the entities if they were alone in the system (i.e., in isolation). Examples of entities are different applications using the wireless interface or processes of interest. However, the actual total consumption of the interface is not the sum of entities' consumption in isolation. Thus, in order to divide the total consumption among the entities, the entities cannot be attributed their energy in isolation. How should we prescribe a share of the total energy consumption to the different entities in the system? Equally dividing the energy consumption would mean that entity 1 subsidises entity 2. Would a proportional apportionment policy be better?

Apportionment scenario 2: We consider a scenario from wireless sensor networks also applicable to an Internet of Things context [9, 12]. Profiling the energy consumption for network nodes in order to quantify the energy consumption of user defined activities (e.g., a query) can support the evaluation of the efficiency of the network or managing energy consumption. The apportionment problem arises when simultaneous activities are present in the system since the energy consumption does not only depend on the active usage of each activity in isolation. The contribution of each activity to the total energy consumption of the sensor nodes (including energy tails or between transmissions) needs to be determined.

Additionally, the total energy consumption of the system is determined by the sum of each node's consumption. However, the contribution of each node to the total consumption is not necessarily its own consumption since a node contributes to other nodes' energy consumption by being part of the system (e.g., transmissions or beacons). Determining the contribution of each node requires a solution to the apportionment problem as well.

In this work we identify the apportionment problem in different areas of computer and communication technologies, ranging over computing [8, 25], data centres [4], mobile devices [6, 15, 16, 18, 23, 35], wireless sensor networks [12, 28], and even energy-efficient buildings [5, 10, 29, 30]. Our work provides an overview of the apportionment problem and identifies relevant areas of study.

The rest of the paper is structured as follows: Section 2 introduces our system model used to reason about the apportionment problem applicable to different contexts as well as the background. Section 3 presents 5 energy apportionment policies. The application context of the policies and the energy accounting approaches are described in section 4, and thus the description of related body of work is merged with our analysis of the selected policies and their contexts. Section 5 discusses the policies in terms of required infor-

mation and categorises the energy accounting approaches. Finally, section 6 concludes our work and provides relevant future directions.

2. NOTATION AND BACKGROUND

In order to formulate the different energy apportionment policies we first introduce our system model and the corresponding notation used in the rest of the paper. We also introduce the apportionment policy definition.

2.1 System model

An energy consuming system is composed by the set of entities $N = \{1, 2, \dots, n\}$ that cause the system which they are part of to consume energy. We distinguish two types of system interpretations: (1) *common resource*, where the entities share a common energy resource, and (2) *individual resource*, where each entity has an energy resource.

Examples of a common resource system are the computers in a datacenter or a battery-powered device shared by different applications, whereas a set of mobile devices or sensor nodes in an ad-hoc or sensor network are systems with individual resources.

2.1.1 Common resource system

$E(N)$ is the *total energy consumption* for a system configuration of the N entities sharing a common resource. We assume that equipment to measure $E(N)$ is available (e.g., measuring the power consumption of a phone by intercepting the battery terminals [32] or the mains connected to a home appliance [5]).

$E(S)$ is the *isolated energy consumption* of the entities in $S \subset N$. Thus, $E(\{i\})$ is the isolated energy consumption of the single entity $i \in N$. $E(\{i\})$ represents the energy consumption of the entity i in the hypothetical case that it was alone in the system, not considering the interaction of the other entities in the system. This quantity is a construct which is estimated (generally not measurable), for example a single application running alone on a mobile device.

2.1.2 Individual resource system

$E_i(N)$ is the *individual energy consumption* of the entity $i \in N$ given a system configuration of entities N . We assume that equipment to measure $E_i(N)$ at each entity i is available. The total system consumption is $\sum_{i \in N} E_i(N)$, e.g., the total consumption of a network of sensor nodes is the sum of nodes' consumption in a network configuration¹.

$E_i(S) : i \in S, S \subset N$, is the individual energy consumption of the entity i given a system configuration of entities S . This is a construct which is estimated (generally not measurable). The total energy consumption for a given $S \subset N$ is $\sum_{i \in S} E_i(S)$.

2.2 Energy apportionment policy

An *energy apportionment policy* Π prescribes the share $\pi_i \in \mathbb{R}$ to an entity $i \in N$ of the total system consumption of the system composed by N entities. A policy may use different input information to apportion the total energy cost among the entities. Equation 1 and 2 define Π for a common and individual resource system respectively:

¹ $E(N)$ is only applicable to the common resource case.

$$\Pi(E(N), N, \dots) = (\pi_1, \pi_2, \dots, \pi_n) \text{ in } R^n \quad (1)$$

$$\Pi(E_1(N), \dots, E_n(N), N, \dots) = (\pi_1, \pi_2, \dots, \pi_n) \text{ in } R^n \quad (2)$$

An apportionment policy should completely apportion the total energy: $\sum_{i \in N} \pi_i = E(N)$ and $\sum_{i \in N} \pi_i = \sum_{i \in N} E_i(N)$ for common and individual resource respectively. This is referred to as *efficiency*.

3. APPORTIONMENT POLICIES

We first categorise energy apportionment policies based on the type of input information. An *energy-based policy* apportions the system energy using different constructs with energy as the only type of input information. A *surrogate-based policy* may employ any type of information except energy. A *hybrid policy* would combine energy and surrogates. In this paper we only consider energy-based policies.

This section surveys 5 of the most used apportionment policies. We briefly describe each policy and provide application examples, which are described in more detail in section 4.

Table 1 provides an overview of the different policies, the type of policy and in which context they have been applied in the literature.

Table 1: Overview of the energy apportionment policies.

Nr.	Name	Context example
1	Equal division	Buildings [10] Wireless sensors [9]
2	Proportional to isolation	Mobile app testing [15, 16, 32] Multi-core CPU [25] Buildings [30]
3	Marginal contribution	Operating systems [24] Multi-core CPU [25] Mobile GUI testing [35]
4	Isolation energy and remainder	Wireless sensors [12] Buildings [10]
5	Shapley value	Mobile devices [6]

3.1 Energy-based policies

This section describes 5 energy-based policies. All policies can be formulated for common and individual resource systems, but due to space limitation and to simplify the presentation we present them using the common resource notation.

All presented policies fulfill efficiency since we have normalised the policies that did not meet this requirement in their original sources (policies 2 and 3).

3.1.1 Policy 1: Equal division

The total energy consumption is divided equally by the number of entities:

$$\pi_i = \frac{E(N)}{|N|} \quad (3)$$

This apportionment policy is regarded as the simplest policy and has been proposed in the context of energy-efficient buildings [10].

3.1.2 Policy 2: Proportional to isolation

The resulting apportionment is proportional to the energy consumption in isolation for each entity. The policy is the same as the pro rata division of $E(N)$ considering the stand-alone energy:

$$\pi_i = \frac{E(\{i\})}{\sum_{j \in N} E(\{j\})} E(N) \quad (4)$$

The policy is proposed for mobile application energy profiling, where the contribution of an application is assumed to be its consumption in isolation [15, 16, 32]. The energy consumption of a multi-core CPU is shared by the different entities in proportion to their usage in isolation (in a single core) [8]. The same idea has been also proposed to share the cost of heating, ventilation, and air conditioning (HVAC) systems [30].

3.1.3 Policy 3: Marginal contribution

This policy considers that the contribution of an entity to the total consumption is its marginal contribution $E(N) - E(N \setminus \{i\})$, i.e., the total consumption when the entity is running minus the consumption when the entity is not running. The policy is normalised using all the marginal contributions:

$$\pi_i = \frac{E(N) - E(N \setminus \{i\})}{\sum_{j \in N} [E(N) - E(N \setminus \{j\})]} E(N) \quad (5)$$

This policy was proposed for operating systems to account for runtime energy consumption of individual system hardware and software entities [24], multi-core systems [25] as well as in mobile devices [35].

3.1.4 Policy 4: Isolation energy and remainder

The policy prescribes the allocation of costs as a function of the energy consumption in isolation plus proportionally dividing the additional cost/benefit of non-isolated use.

$$\pi_i = E(\{i\}) + \frac{E(N) - \sum_{j \in N} E(\{j\})}{|N|} \quad (6)$$

This policy is originated in the energy-efficient building community [10], where the personal consumption is estimated first and the rest is divided evenly (e.g., base energy load of building elements such as HVAC). Similarly, in the context of wireless sensor networks, the energy cost of messages received by a certain task is prescribed to the task and the rest (e.g., synchronisation or message loss) is shared evenly among the tasks [12].

3.1.5 Policy 5: Shapley value

Given the marginal contribution of i to a coalition $S \subseteq N \setminus \{i\}$ given by $E(S \cup \{i\}) - E(S)$, the *Shapley value* computes the average marginal contribution of i averaging over all the possible sequences through which the grand coalition can be built from the empty coalition [27]:

$$\pi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(|N| - |S| - 1)!}{|N|!} [E(S \cup \{i\}) - E(S)] \quad (7)$$

The Shapley value is a well known single value solution from cooperative game theory applied to many cost sharing problems in computer science [14, 26] as well as in other fields [7]. Recently it has been argued to be the ground truth for energy accounting in mobile devices [6].

4. ENERGY APPORTIONMENT APPLICATIONS

This section is devoted to describe the application of the above presented energy apportionment policies. We briefly explain each approach, analyse and report which policies they employ. The works are categorised in four different contexts: processing and operating systems, wireless sensor networks, energy-efficient buildings and mobile devices.

4.1 Processing and operating systems

PowerScope [8] is a work from 1999 that aims to map energy consumption to program structure by employing physical power measurements combined with kernel level system activity information. The work considers a single-core CPU (only a single process can be executed simultaneously) and attributes a process the energy consumed when this is being executed.

The work by Neugebauer and McAuley [16] discusses the difficulties in estimating the consumption of each entity due to asynchronous energy overheads (e.g., energy tails). They propose that the apportionment should be done in proportion to usage surrogates, such as the access time to a resource, the number of pixels used in a display or the transmitted data traffic.

Ryffel et al. [25] and LEA²P [24] extend the idea of PowerScope to multi-core systems where processes can run contiguously. Policy 3 (Marginal contribution) is used to attribute the total energy consumption of the system to processes. However, obtaining the energy consumption values is not feasible for some system components such as CPU since processes run simultaneously. They propose to employ indirect information based on performance counters in addition to power measurements to model energy consumption. Then, they use Policy 2 (Proportional to isolation) to estimate the apportionment cost of each process for the CPU based on what they consumed in isolation. Policy 3 is said to be fair without any formal justification or evidence.

Joulemeter [11] is a system to attribute the energy consumption of a cloud server to the running virtual machines (VMs). The energy consumption of each VM is estimated based on measurement-based energy models and it is argued that if the sum of the estimated energy is equal to the total measured energy (i.e., efficiency) the apportionment is correct, which is not always the case. Similar to the previous work, they propose to consider the energy in isolation as the apportionment for each VM (similar to Policy 2).

4.2 Wireless sensor networks

Quanto [9] is an energy profiler for network nodes which combines energy metering hardware and program activity information to quantify the energy consumption for user defined activities. They use the notion of activity as a logical set of operations whose resource usage is grouped together in order to help the developer understand the energy expenditure. An entity is a similar notion in our work.

By tracking the power state change events at driver level Quanto estimates the energy breakdown of the different components, and then the system quantifies resource consumption of the activities. While a single-activity device is considered leading to a straightforward apportionment, they mention that the apportionment for a multiple-activity device is

a policy decision and preliminary select to divide the energy consumption equally, i.e., in a similar way to Policy 1.

Kellner [12] considers the context of dynamic sensor networks where various applications can query a sensor network at any point in time. The work proposes a online energy accounting system employing measurement-based finite state machine (FSM) models to attribute energy consumption to tasks. Since energy consumption does not only depend on the active usage (e.g., energy tails or between uses), the author identifies several ways to divide the remainder energy. Policy 4 (Isolation energy and remainder) is applied to message reception where the cost of the messages which cannot be attributed directly to any task are equally shared.

4.3 Energy-efficient buildings

A first and influential work by Hay and Rice [10] formulate the problem of attributing the energy consumption of a building or organisation to individual users and identify two requirements that a policy should satisfy: completeness (i.e., efficiency) and accountability, meaning that the actions of a user should have a maximal effect on their own share and a minimal on the rest of users. Policy 1 (Equal division) is proposed as the most basic policy, which is further developed using occupancy time as a surrogate of energy. Policy 4 (Isolation energy and remainder) is then proposed by first calculating the personal load of a user and then dividing the rest evenly. Their efforts then focus on estimating the personal load more accurately employing sensors.

Similarly, WattShare [29] aims to attribute the energy consumption of a shared building to individual occupants (*personal apportionment*). Considering only the availability of the total energy consumption measured at the smart meter, their work proposes to employ smartphones carried by the occupants to perform the apportionment by estimating the electrical events (e.g., use of a TV) created by each user.

In the same context, Tsao et al. [30] investigate how to attribute the energy cost of centralised heating, ventilation and air conditioning system to different rooms in a building. They propose to employ Policy 2 (Proportional to isolation) and argue that it satisfies efficiency and accountability. There is no evidence showing that their apportionment approach satisfies the two properties.

4.4 Mobile devices

Pushed by short battery lifetimes energy profiling has attracted a great attention in mobile devices to improve software energy efficiency. Our previous work EnergyBox [32] develops a FSM-based energy model for wireless interfaces. By isolating the traffic of an application the energy efficiency of the applications is studied in isolation using EnergyBox [1, 31]. Other studies perform a similar simplifying assumption to profile the energy consumption due to communication [20, 22, 33] which is similar to Policy 2 (Proportional to isolation).

Similarly, WattsOn [15] is a system to estimate the energy consumption by an application at the development environment which reuses and slightly extends previously developed FSM-based energy models. This work considers that the energy consumption of the application is the total energy consumption of the system when only the application is running (i.e., similar to Policy 2).

Policy 3 (Marginal contribution) is employed to obtain the energy contribution of graphical user interfaces with a focus

on optimising energy consumption from hardware, software and application perspective [35].

Eprof [18] is an energy profiler for smartphones that employs system call-based resource usage information and FSM-based models to attribute the energy consumption to applications (and activities within the application) for efficient application development. They discuss different alternatives to attribute the energy consumption of energy tails such as equally (Policy 1) or proportionally dividing the energy cost among the consuming entities (Policy 2). Finally, they propose to apportion the energy consumption of an energy event to the last entity that used a resource in order to incentivise the developer to batch energy events.

The recent work by Dong et al. [6] is the first work considering the application of cooperative game theory in the context of mobile energy accounting. Policy 5 (Shapley value) is argued to be the ground truth for the apportionment problem and they focus on providing an approximation of it. Using physical power measurements they define every 10 millisecond interval as a game where the energy consumption needs to be attributed to the active entities. By considering these short intervals they attempt to observe the consumption of different coalitions (i.e., observing intervals where only some entities are active) and employ a combination of the observed coalitions with hardware states (for WiFi and CPU) to reduce the variance of the observations. The unobserved coalitions are statistically estimated from historical data. Their results show that other accounting methods differ from their approach.

The presented applications of energy apportionment show the relevance of the problem in different fields and emphasises the need for unifying and analysing approaches towards energy efficiency.

5. DISCUSSION

In this section we preliminarily look at two different general aspects in the following subsections: required information and energy accounting approach.

5.1 Required information

The presented policies require different amounts of input information to perform the apportionment and obtaining this information might be harder depending on the system context.

Policy 1 employs the minimum input quantity: $E(N)$ and N . Policies 2, 3 and 4 require the energy consumption of $|N|$ subsets. Policies 2 and 4 consider the energy in isolation $E(\{i\})$ and 3 considers the system energy excluding a single entity $E(N \setminus \{i\})$. Policy 5 presents the highest information requirement, requiring the energy consumption of all the subsets of N ($2^{|N|}$).

Thus, depending on the available information for a system some policies seem more appealing than others.

5.2 Energy accounting approaches

Based on the applications of energy accounting surveyed in section 4, we distinguish two general approaches: bottom-up and top-down. Note that these are not necessarily related to the policy categorisation, since one refers to apportionment policies and the other to the accounting approach.

A common approach in energy accounting is to employ energy models of the different resource components in the

system to estimate the contribution of each entity of interest to the total energy consumption. Most works [11, 15, 18] adopt a bottom-up approach where the total energy consumption is constructed employing the estimated energy of the components. Then, the energy is often apportioned to the entity as the sum of the contribution to each component using one of the described policies.

The advantage of modelling energy is that estimating $E(S)$ can be done directly with the energy models without requiring external measurements. Additionally, the bottom-up approach attributes energy consumption to each component providing excellent visibility and useful information for optimising software.

One of the major disadvantages of the bottom-up approach is that if the energy models (E function) are not accurate the difference is propagated in the apportionment and can lead to an apportionment not satisfying efficiency. It is trivial to see that if $E(N)$ is not measured and the estimation is not correct, it will lead to a difference in the apportionment. When physical power measurements are available, a policy will satisfy efficiency by normalising the modelled energy consumption to the measured consumption (i.e., like we did for Policies 2 and 3). However, the difference will still propagate the uncertainty in the apportionment.

The top-down approach employs power measurements and divides the total energy consumption [6, 8]. Thus, it always satisfies efficiency. However, estimating the energy consumption of $E(S)$ is difficult and its approximation introduces uncertainty in the apportionment as well. These approaches often provide less information about component consumption per entity.

We believe that a combination of both approaches is interesting to study since a hybrid approach can benefit the system by providing visibility useful for software optimisation as well as an efficient apportionment. Studying the impact of the energy model accuracy or $E(S)$ estimation on the apportionment is also relevant.

6. CONCLUSIONS AND FUTURE WORK

Our work has shown that the energy apportionment is a relevant problem in different fields such as operating systems, mobile devices, energy-efficient buildings and wireless sensor networks and emphasised the need for unifying and analysing the proposed approaches. In this paper we categorised and described a total of 5 different energy apportionment policies.

Based on the method used to perform energy accounting, we also distinguished a top-down and a bottom-up approach. A combination of both approaches is suggested to preserve the efficiency of the apportionment while still providing visibility of system's resource consumption.

Extensions to this work include analysing the impact of the information requirements in the computational complexity of the policies and the type of input information. Fairness considerations are an important aspect that deserves further study. Many of the presented apportionment policies were said to be fair or developed to provide incentives without any formal analysis. Finally, developing means to measure or better approximate the system function is a key capability for any energy apportionment policy.

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7. REFERENCES

- [1] M. Almquist, V. Almquist, E. J. Vergara, and S. Nadjm-Tehrani. Communication energy overhead of mobiles games. In *Proceedings of the 2nd Workshop on Mobile Gaming*, MobiGames '15, pages 1–6. ACM, 2015.
- [2] K. Athukorala, E. Lagerspetz, M. von Kügelgen, A. Jylhä, A. J. Olinier, S. Tarkoma, and G. Jacucci. How Carat Affects User Behavior: Implications for Mobile Battery Awareness Applications. In *Proceedings of the ACM Conference on Human Factors in Computing Systems*, CHI '14, pages 1029–1038. ACM, 2014.
- [3] N. Balasubramanian, A. Balasubramanian, and A. Venkataramani. Energy consumption in mobile phones: A measurement study and implications for network applications. In *Proceedings of the 9th ACM SIGCOMM Conference on Internet Measurement Conference*, IMC '09, pages 280–293. ACM, 2009.
- [4] R. Bertran, Y. Becerra, D. Carrera, V. Beltran, M. Gonzalez Tallada, X. Martorell, J. Torres, and E. Ayguade. Accurate energy accounting for shared virtualized environments using PMC-based power modeling techniques. In *IEEE/ACM International Conference on Grid Computing*, pages 1–8, Oct 2010.
- [5] Y. Cheng, K. Chen, B. Zhang, C.-J. M. Liang, X. Jiang, and F. Zhao. Accurate real-time occupant energy-footprinting in commercial buildings. In *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, BuildSys '12, pages 115–122. ACM, 2012.
- [6] M. Dong, T. Lan, and L. Zhong. Rethink energy accounting with cooperative game theory. In *Proceedings of the 20th Annual International Conference on Mobile Computing and Networking*, MobiCom '14, pages 531–542. ACM, 2014.
- [7] M. Fiestras-Janeiro, I. García-Jurado, and M. A. Mosquera. Cooperative games and cost allocation problems. *TOP*, 19(1):1–22, 2011.
- [8] J. Flinn and M. Satyanarayanan. PowerScope: A Tool for Profiling the Energy Usage of Mobile Applications. In *Proceedings of the 2nd IEEE Workshop on Mobile Computer Systems and Applications*. IEEE, 1999.
- [9] R. Fonseca, P. Dutta, P. Levis, and I. Stoica. Quanto: Tracking energy in networked embedded systems. In *Proceedings of the 8th USENIX Conference on Operating Systems Design and Implementation*, OSDI'08, pages 323–338. USENIX Association, 2008.
- [10] S. Hay and A. Rice. The case for apportionment. In *Proceedings of the First ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, BuildSys '09, pages 13–18. ACM, 2009.
- [11] A. Kansal, F. Zhao, J. Liu, N. Kothari, and A. A. Bhattacharya. Virtual machine power metering and provisioning. In *Proceedings of the 1st ACM Symposium on Cloud Computing*, SoCC '10, pages 39–50. ACM, 2010.
- [12] S. Kellner. Flexible Online Energy Accounting in TinyOS. In *Proceedings of the 4th International Workshop on Real-World Wireless Sensor Networks*, volume 6511 of *LNCS*, pages 62–73. Springer, 2010.
- [13] J. Lemaire. An application of game theory: Cost allocation. *ASTIN Bulletin*, 14:61–81, 4 1984.
- [14] V. Misra, S. Ioannidis, A. Chaintreau, and L. Massoulié. Incentivizing Peer-assisted Services: A Fluid Shapley Value Approach. In *Proceedings of the ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems*, SIGMETRICS '10, pages 215–226. ACM, 2010.
- [15] R. Mittal, A. Kansal, and R. Chandra. Empowering Developers to Estimate App Energy Consumption. In *Proceedings of the 18th Annual International Conference on Mobile Computing and Networking*, Mobicom '12, pages 317–328. ACM, 2012.
- [16] R. Neugebauer and D. McAuley. Energy Is Just Another Resource: Energy Accounting and Energy Pricing in the Nemesis OS. In *Proceedings of the Eighth Workshop on Hot Topics in Operating Systems*, HOTOS '01. IEEE, 2001.
- [17] A. Papathanasiou and M. Scott. Energy efficiency through burstiness. In *Fifth IEEE Workshop on Mobile Computing Systems and Applications*, pages 44–53, Oct 2003.
- [18] A. Pathak, Y. C. Hu, and M. Zhang. Where is the Energy Spent Inside My App?: Fine Grained Energy Accounting on Smartphones with Eprof. In *Proceedings of the 7th ACM European Conference on Computer Systems*, EuroSys '12, pages 29–42. ACM, 2012.
- [19] J. E. Petersen, V. Shunturov, K. Janda, G. Platt, and K. Weinberger. Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives. *International Journal of Sustainability in Higher Education*, 8:16–33, 2007.
- [20] F. Qian, Z. Wang, A. Gerber, Z. Mao, S. Sen, and O. Spatscheck. Profiling resource usage for mobile applications: A cross-layer approach. In *Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services*, MobiSys '11, pages 321–334. ACM, 2011.
- [21] A. Reinhardt, P. Baumann, D. Burgstahler, M. Hollick, H. Chonov, M. Werner, and R. Steinmetz. On the accuracy of appliance identification based on distributed load metering data. In *Sustainable Internet and ICT for Sustainability (SustainIT)*, 2012, pages 1–9, Oct 2012.
- [22] A. Rice and S. Hay. Measuring mobile phone energy consumption for 802.11 wireless networking. *Pervasive Mobile Computing*, 6(6):593–606, Elsevier. Dec. 2010.
- [23] A. Roy, S. M. Rumble, R. Stutsman, P. Levis, D. Mazières, and N. Zeldovich. Energy Management in Mobile Devices with the Cinder Operating System. In *Proceedings of the Sixth Conference on Computer Systems*, EuroSys '11, pages 139–152. ACM, 2011.
- [24] S. Ryffel. LEA²P: The Linux Energy Attribution and Accounting Platform. Master's thesis, Swiss Federal Institute of Technology, 2009.
- [25] S. Ryffel, T. Stathopoulos, D. McIntire, W. Kaiser, and L. Thiele. Accurate energy attribution and

accounting for multi-core systems. Technical report, Center for Embedded Network Sensing, University of California, Sept. 2009.

- [26] M. Sereno. Cooperative game theory framework for energy efficient policies in wireless networks. In *Proceedings of the 3rd International Conference on Future Energy Systems: Where Energy, Computing and Communication Meet*, e-Energy '12, pages 17:1–17:9. ACM, 2012.
- [27] L. S. Shapley. A value for n-person games. *Contributions to the theory of games*, 2:307–317, 1953.
- [28] A. Sieber and J. Nolte. Online device-level energy accounting for wireless sensor nodes. In *Proceedings of the 10th European Conference on Wireless Sensor Networks*, pages 149–164. Springer-Verlag, 2013.
- [29] S. Thakur, M. Saha, A. Singh, and Y. Agarwal. Wattshare: Detailed energy apportionment in shared living spaces within commercial buildings. In *Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings*, BuildSys '14, pages 30–39. ACM, 2014.
- [30] Y.-t. Tsao, C.-C. Huang, and J. Y.-j. Hsu. Demand-based apportionment on electricity payment of hvac systems. In *Proceedings of the 2014 International Conference on Autonomous Agents and Multi-agent Systems*, pages 1601–1602, 2014.
- [31] E. J. Vergara, S. Andersson, and S. Nadjm-Tehrani. When mice consume like elephants: Instant messaging applications. In *Proceedings of the 5th International Conference on Future Energy Systems*, e-Energy '14, pages 97–107. ACM, 2014.
- [32] E. J. Vergara, S. Nadjm-Tehrani, and M. Prihodko. EnergyBox: Disclosing the wireless transmission energy cost for mobile devices. *Sustainable Computing: Informatics and Systems*, 4(2):118–135, Elsevier. 2014.
- [33] Y. Xiao, R. Kalyanaraman, and A. Yla-Jaaski. Energy consumption of mobile YouTube: Quantitative measurement and analysis. In *Proceedings the 2008 Second International Conference on Next Generation Mobile Applications, Services and Technologies*, NGMAST '08, pages 61–69. IEEE, Sept. 2008.
- [34] H. Zeng, C. S. Ellis, A. R. Lebeck, and A. Vahdat. ECOSystem: Managing Energy As a First Class Operating System Resource. *SIGOPS Oper. Syst. Rev.*, 36(5):123–132, Oct. 2002.
- [35] L. Zhong and N. K. Jha. Graphical user interface energy characterization for handheld computers. In *Proceedings of the 2003 International Conference on Compilers, Architecture and Synthesis for Embedded Systems*, CASES '03, pages 232–242. ACM, 2003.