Energy-efficient Peer-to-Peer Networking for Constrained-Capacity Mobile Environments

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***Abstract*— Energy efficiency is a powerful measure for promoting sustainability in technological evolution and ensuring feasible battery life of mobile end-user devices. Peer-to-peer technology provides decentralized and self-organizing, but also energy-inefficient technology for distributing content between devices in networks that scale up almost infinitely. The dissertation summarized in this paper [1] makes four contributions towards enabling energy-aware peer-to-peer networking in mobile environments: 1) an empirical study for understanding the energy consumption characteristics of radio interfaces and typical composition of traffic in peer-to-peer networks, 2) a model for estimating the energy consumption of a mobile device with different traffic profiles, 3) a model for energy-aware load monitoring of mobile peer nodes, and 4) a mobile agent based virtual peers concept for energy-aware sharing of peer responsibilities between peer nodes in a subnet. The results give valuable insight into implementing energy-efficient peer-to-peer systems in mobile environments.**

Keywords—peer-to-peer, mobile agent, machine-to-machine, internet-of-things, energy-efficiency

I. Introduction

The role of Information and Communications Technology (ICT) in promoting sustainability in technological evolution and ensuring feasible battery life of end-user devices is twofold. On the one hand, ICT is one of the main tools for improving the energy-efficiency of the infrastructures around us [2]. On the other hand, ICT's intrinsic energy demand is rising rapidly [3]–[4]. As a consequence, the significance of green computing is growing.

A growing share of Internet nodes are mobile (battery-powered) devices, such as mobile phones, tablets, and various wireless Internet of Things (IoT) nodes [5]–[6]. Along with the requirements for sustainability and overall energy-efficiency, maintaining feasible battery life sets strict requirements for the energy consumption of mobile devices. Battery life is recognized as one of the most centric factors of long-term user experience of mobile devices [7]–[9]. Furthermore, the requirements concerning the physical size and capacity of batteries have become stricter due to the size miniaturization and growing performance requirements, while at the same, time more and more advanced hardware and software require more energy [10]. Thus, improving energy-efficiency is a cost-efficient way to improve battery life of mobile devices.

An increasing share of mobile content is stored outside the end-user device, in order to save local storage space or to share or backup the content. At the same time, the supporting infrastructure has to scale up at the same pace to support the growing capacity demand. Related to this, the virtualization of software, content, services and infrastructures is one of the current megatrends in ICT [5][6][11]. Cloud computing is one of the most widespread virtualized technology, providing a scalable infrastructure for service providers and relieving them from expensive and time-consuming investments to the service infrastructure.

Peer-to-Peer (P2P) technology provides a scalable option for distributing content between devices in networks that scale up almost infinitely [12]. Today, P2P technologies are used in virtualized systems for optimizing content delivery and distributing computational load [13]–[16]. P2P networks are known for their superior scalability: since computational resources are provided by participating end-user devices, the system resources inherently scale up with network size.

The above-mentioned trends emphasize the need for developing P2P systems that are suitable for mobile use. The integration of mobile and P2P systems is very challenging, due to two reasons. Firstly, the use of P2P technologies can significantly increase the energy consumption of mobile devices. Distributed content management and network maintenance require frequent messaging and data transfers among peer nodes in the background, even when devices are otherwise idle. This is problematic for mobile devices and networks since frequent signaling keeps the mobile radio interface active almost continuously, and thus, significantly increases their energy consumption [17]–[18]. Secondly, while operating in P2P networks, the special characteristics of mobile networking cause problems related to routing integrity, Quality of Service (QoS) properties and energy-efficiency on the system level [20]. Power saving functions, mobility and limitations in network coverage makes the online presence of mobile devices transient in its nature. The resulting frequent leaving and joining of nodes increases the need for network maintenance signaling [21]–[23]. This is a major issue in mobile P2P networking, where maintenance signaling is a significant source of energy consumption.

The dissertation [1] focuses on addressing the following research questions in the context of mobile P2P networking:

- How different traffic patterns and network topologies affect the energy consumption of a mobile device?
- What load monitoring methods can be used to exploit energy-awareness in load distribution among peer nodes and how much energy can be saved in mobile peer nodes using these methods?
- What load balancing methods can be used to reduce constrained-capacity mobile peer node resource usage and how much energy can be saved using these methods?

The rest of the paper is organized as follows. Section II presents the background for the thesis. The main contributions are presented in Section III and Section IV concludes the work.

II. Background

A. Peer-to-Peer Networking

P2P systems are distributed systems that operate without centralized organization or control [12]. The participating devices form an overlay network of logically linked peer nodes that provide the needed routing, computing and storage resources for the system. The topology of the overlay network is independent of the topology of the lower network layers. The main function of the overlay network is to provide participating nodes a decentralized method to find each other and different resources made available on the system. These resources can be files, programs, media streams, contact information, etc.

The *index* is the data structure used for locating nodes or shared resources in a P2P network. It can be maintained by a single node (*centralized*) or it can be distributed among all peers (*distributed*) or a subset of peers (*hybrid*) [12][24]. When centralized index is used, the location of a resource is requested from the index node and the resource is then acquired from the node storing the resource, based on the location information. With distributed or hybrid index, the location of the requested resource is looked up based on either a distributed algorithm, such as Distributed Hash Table (DHT) (*structured* P2P networks), random selection of recipients or flooding (*unstructured* P2P networks) [12]. When the location information is found, the resource is acquired from the storing node based on the location information.

B. Key Challenges of P2P networking in Mobile Systems

A predominant challenge for P2P networking in mobile environment is the limited hardware capacity of nodes [20], [25][26]. In addition to *lower computing performance* and *network throughput*, there are also differences in *network latency* and *communication range*. Also *limited battery life* affects the above mentioned features through strict energy saving requirements [17]. The *transient nature of mobile device online presence*, that is caused by, e.g., power saving functions, the user interventions, or limitations in the network coverage, affects negatively the operation of P2P networks [20]. The *restricting policies and technologies* used by the network operators is another major challenge for P2P networking in mobile environment. Most of today's mobile devices have private IP addresses and they are behind firewalls that hinder their direct connectivity with nodes outside the operator network and may significantly limit the number of allowed protocols and their performance [27].

Overall, the limited battery life is already a widely known problem with smartphones, and the utilization of P2P technologies makes the situation even more problematic due to increased maintenance messaging load, also during the idle periods. This maintenance messaging may drain the battery of a mobile device in only a few hours. Thus, optimization mechanisms that would reduce the burden on mobile peer nodes in P2P networks are needed.

C. Energy-Efficiency of Mobile Networking

Majority of the energy consumption in mobile and IoT nodes originates from communications [28]–[29]. Consequently, the emphasis of the thesis is on the energy-efficiency of communications. The traditional energy-efficiency optimizations in mobile computing and communications include hardware and firmware level optimizations in radio interfaces and computing architectures, such as adaptive transmission power management and duty cycling. These technologies have been utilized in most of the currently used cellular radio technologies, such as 3G [17]], [30], 4G [31][32] and WiFi[17], [30], [33]–[34], as well as short-range IoT [30], [35][37] radio technologies. To maximize energy-efficiency, higher-layer solutions must exploit these features as efficiently as possible. Approaches such as optimizing traffic patterns [32], [38] and offloading computation to more capable nodes [39]–[40], have been proven effective application-layer solutions in reducing the energy consumption of mobile devices.

D. Load Balancing in P2P Systems

Load balancing is a method for distributing computational tasks fairly between nodes in a distributed network, i.e. utilizes computational offloading, in order to avoid situations where some nodes or links would experience much heavier load than others. Load balancing, illustrated in Fig. 1, can be described as a process consisting of three distinguishable components: *load monitoring* for defining a node's load, *load information exchange* for enabling load comparison between nodes, and *load migration* for realizing the load balancing decisions.

Fig. 1. Load balancing process.

Various different load balancing mechanisms have been proposed for P2P systems. Felber et al. [41] provide a thorough survey of different load balancing methods for P2P systems, focusing on load information exchange and load migration. In addition to load information exchange and load migration, load monitoring is a centric element for resource-aware (energy-aware) load balancing. Traditional method for monitoring the load of a node is measuring how much service load (service requests, transactions, downloads etc.) or hardware load (CPU, memory, network) a node carries. Furthermore, some advanced load monitoring mechanisms that combine different load metrics have been proposed, such as [43], [44] and [45]. However, it seems that the related work on energy-aware load monitoring and balancing in P2P context is practically non-existent. In order to facilitate the participation of battery-powered devices, heterogeneity in hardware resources and energy characteristics has to be better taken into account. The thesis focuses on filling this gap.

III. Contributions of the Thesis

The thesis comprises of six peer-reviewed scientific papers [18], [30], [46]–[49], categorized into four main contributions that are presented in the following subsections.

A. Empirical Feasibility Analysis of Mobile P2P Networking

Papers I [46] and II [18] provide an empirical study to identify the energy consumption characteristics of the most widely used mobile wireless radio technologies. The measurement results of Paper I reveal a non-linear correspondence between data rate and power consumption. The phenomenon was found to originate from the various states used by the radio interfaces in order to save energy. Fig. 2 presents the measurement results for (a) 3G and (b) WLAN radio interface. Paper II extends the study with a more detailed analysis on the combined effect of different sending intervals and packet sizes on the energy consumption of the mobile devices. The evaluations provide an insight into the energy consumption effects of different radio interface states for 3G and WLAN communication technologies.

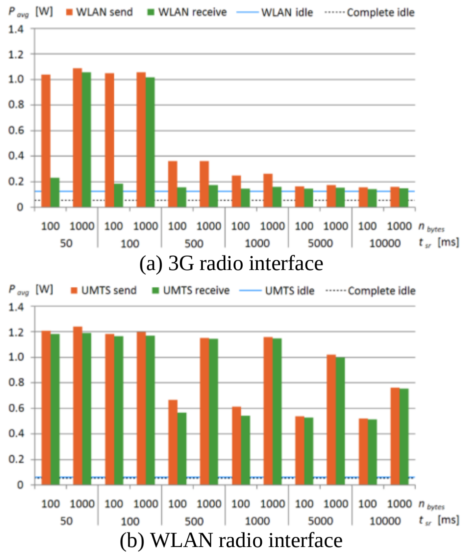


Fig. 2. Energy consumption profiles for a smartphone [46].

Paper III [47] continues the empirical study by providing a breakdown of the traffic for a P2P node running two popular DHT algorithms, Kademlia and Chord, and comparing their performance and efficiency. As a result, Paper III provides valuable information on the composition of the signaling traffic and common traffic patterns of structured P2P networks. A centric observation was that the maintenance signaling dominates the traffic with both DHT algorithms. Furthermore, the average message transmission interval was found relatively short and the message sizes relatively small with both DHT algorithms. The study also provided valuable information on the effect of overlay parameters on the message transmission interval and lookup efficiency.

Together, Papers I–III establish an empirical basis for defining energy consumption profiles for a mobile device connected to 3G and WLAN radio interfaces and traffic profiles for structured P2P overlay networks. The models for energy consumption optimization proposed in Papers IV [30], V [48] and VI [49] are based on the empirical basis established in Papers I–III.

B. e-Aware – Energy Consumption Model

Paper IV [30] introduces the *e-Aware* model for estimating how application layer properties affect the energy consumption of mobile devices operating in mobile networks. The model estimates the energy consumption originating from network operations based on two energy consumption elements, *signaling* and *media* transfers. The distinction between signalling and media transfers is made due to their different energy consumption characteristics that were studied in Papers I–III. The model takes as parameters the transmission interval and packet size for transferred data chunks smaller than 1500 bytes and the amount of moved data for data chunks greater than 1500 bytes. Power and energy consumption estimates are produced as output for a given scenario. The model calculates the total energy consumption estimation as a sum of energy consumption originating from signalling (data chunks under 1500 bytes) and from media transfers (data chunks over 1500 bytes) (Eq. 1). The details of the model are presented in Paper IV [30].

$$\mathrm{P}(t) = \max[P_{sig}(t), P_{med}(t)] \quad (1)$$

For signalling, the model simulates the power consumption of a mobile device with different network interfaces using a set of equations based on the state machines of the wireless protocols and the empirical power consumption measurement data gathered in Papers I–II. In addition to the traffic parameters, the algorithm uses network-specific parameters, such as timeout intervals, packet size thresholds and practical upload/download transfer rates. Fig. 3 (a) shows a typical power consumption curve with 3G radio interface for packets sized below 250 Bytes, and Fig. 3 (b) shows the curve for packets above 250 Bytes in 3G. Fig. 3 (c) shows the similar curve for WLAN networks with all packet sizes.

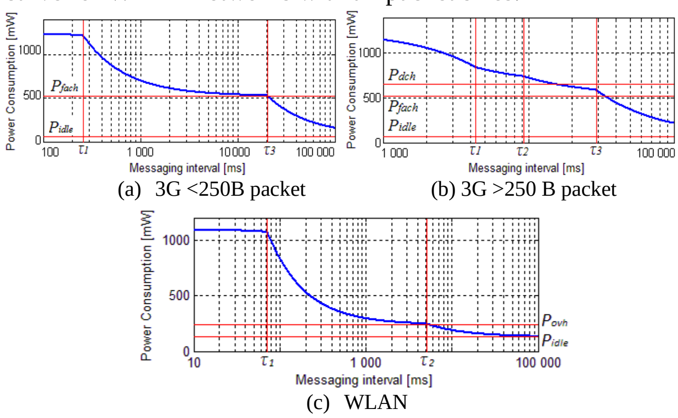


Fig. 3. Estimated power consumption for signalling in 3G and WLAN networks [30].

For full data-rate transfers, the model first calculates the data transfer time (t_{tra}), including the setup time, by using the size of the moved data object and the practical upload/download data transfer rates given as parameters. During t_{tra}, the power consumption is averagely P_{ul} for uploads or P_{dl} for downloads, after which the power consumption returns to P_{idle} through intermediate power states. P_{ul}, P_{dl} and P_{idle} are defined based on the measurements of Papers I–II.

According to the results, the accuracy of the e-Aware model is high in application scenarios where the traffic consists of frequently sent packets with low variance in packet sizes (3-6% estimation error) and full-bandwidth data transfers (< 1% estimation error). When the packet sizes vary significantly, the accuracy was found lower, but still acceptable (14–21% estimation error). The e-Aware model was found to have strong potential to facilitate the development of energy-efficient networking solutions by reducing the need for time-consuming iterations between system development and evaluations with real-life networks and devices.

C. e-Mon – Energy-aware Load Monitoring Model

Paper V [48] proposes the *e-Mon* load monitoring model for enabling energy-aware load balancing in P2P networks. It includes the energy status of a peer node as one of the load factors used in defining the load of a peer node.

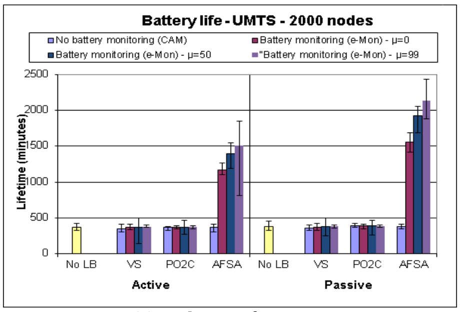
$$L_n = \sum_{i=1}^{N} \omega^i L_n^i, \qquad (2)$$

$$L_n^{bat} = \mu + \frac{100-\beta_n}{100/(100-\mu)}, 0 \le \mu < 100 \qquad (3)$$

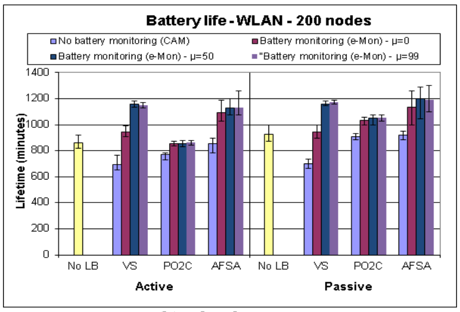
e-Mon calculates the load of a node L_n as a weighed sum ω^i of different load factors L_n^i, as shown by Eq. 2. As a default, e-Mon uses communication load, computational load and battery load as default load factors. However, the load factors are not limited to the three mentioned. Instead, other load factors, such as memory allocation, storage utilization, and I/O operations, can be used as well. Computational and communication load values are obtained by using exponentially averaged CPU and communication channel utilization. For battery load (L_n^{bat}), the model uses 0 as the battery load value for AC-plugged devices and the remaining battery percentage β_n for calculating the battery load devices running on their batteries, as shown by Eq. 3. The μ-parameter adjusts the balance of to what extent being battery powered and remaining battery capacity affect the battery load.

e-Mon was evaluated by comparing its performance with three different load balancing models, including Virtual server (VS), Power of two choices (PO2C) and Advanced Finger Selection (AFSA), in three different setups: 1) a setup with load balancing equipped with e-Mon, 2) a setup without load balancing and 3) a setup with load balancing but without battery monitoring. The comparison reveals the total gain in battery life when e-Mon is in use and details the contribution of battery load monitoring. The evaluation was conducted with two application scenarios having different usage profiles: 1) video conferencing (Fig. 4 (a)), and 2) mobile cloud storage (Fig. 4 (b)).

The results demonstrate that the model can significantly improve the battery life of mobile nodes by improving the quality and fairness of load balance between heterogeneous nodes. e-Mon achieved up to 470% battery life extension compared to the case with battery monitoring deactivated. The impact of e-Mon was most visible with AFSA load balancing, where the battery life was extended by 17–470% depending on the application scenario and used parameters. With VS load balancing, the use of e-Mon improved the battery life by 1–68%. The effect of e-Mon on the overall performance of VS load balancing was weaker than with AFSA due to the massive overlay maintenance overhead inflicted by VS. With PO2C load balancing, the use of e-Mon improved the battery life by 9–30% in the mobile cloud storage scenario. In the video conferencing scenario, the use of PO2C could not bring any energy savings. This is explained by the fact that PO2C cannot influence the load originating from the overlay maintenance signaling that is the dominant traffic type in the video conferencing scenario.



(a) Video conferencing



(b) Cloud storage

Fig. 4. Battery life of a mobile smartphone in different scenarios [48].

The results also revealed that using higher μ-parameter values helps a battery-powered device to adapt faster to the changed energy status when it is plugged off the external power source. Despite the increased load-balancing overhead, the battery life typically improved by 10–20% in the evaluated scenarios when μ-parameter was adjusted from minimum (0) to maximum value (99).

D. ADHT – Mobile Agent-based Virtual Peer Concept

Paper VI [49] proposes the novel concept, named *ADHT*, for facilitating the participation of constrained-capacity wireless devices in P2P networks by allowing them to sleep for most of their time. So far, only super-peer based architectures have allowed some of the P2P nodes to enter sleep mode when connected to P2P network by allocating one node in a cluster as a super-peer node while the others have been ordinary peer nodes that can sleep when no activity is required from them. However, the super-peer model is problematic if all nodes in the subnet are battery-powered constrained-capacity nodes: if the super-peer node would be one of the constrained-capacity nodes in a M2M cluster, its battery life would most likely become unfeasibly short. ADHT prevents this problem by rotating the peer agent, which role is equivalent to super-peer node, between the peer nodes.

In the ADHT concept, one node among the *sub-peer* nodes (i.e. nodes allocated for acting as a peer node when needed) in a subnet takes care of the peer responsibilities while the other nodes are either in sleep mode or act as ordinary peer nodes. As illustrated in Fig. 5, the peer functionality is encapsulated in a mobile agent as a virtual peer node, called *peer agent*. The peer agent is rotated between the sub-peer nodes, based on a *peer allocation algorithm*. The mobile agent is composed of *code*, *resource* and *state* segments. The code segment contains the executable codes, including the DHT algorithm and the peer allocation algorithm. Since the data stored in a P2P system is located at the end nodes, the data management within the subnet has to be taken into account when the peer responsibility is shared. For this, ADHT provides three *data delivery modes* with different characteristics concerning the data freshness and hardware resource consumption.

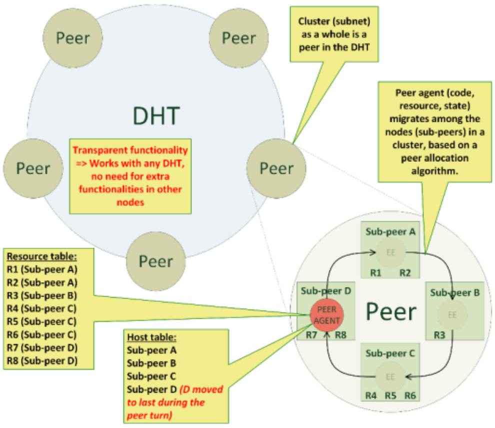


Fig. 5. Overview of the ADHT architecture [49].

The power consumption characteristics of ADHT was analysed and compared with alternative architectures. The table summarizing the power consumption of peer nodes in ADHT and traditional architectures is presented at the end of Paper VI [49]. The power savings were significant compared to the flat P2P architecture. The most important difference is, however, the even distribution of the load among subnet nodes over the time. The benefit is especially clear compared to the traditional super-peer architecture, where the (static) super-peer node consumes up to 450mW while the ordinary peer nodes consume only 30mW. It is obvious that if the super-peer node is one of the constrained-capacity nodes in a M2M cluster, its battery life would be unfeasibly short. Thus, ADHT has a great potential to solve the super-peer overload problem, as compared with the most feasible existing architecture.

IV. Conclusion

The dissertation summarized in this paper explored mechanisms for enabling energy-aware P2P networking to facilitate the use of P2P systems in mobile environments.

First, the thesis commenced with an empirical study to understand the energy consumption characteristics of radio interfaces and typical composition of traffic in structured P2P networks. This was done in order to identify the most essential obstacles for utilizing P2P technology in mobile environments. The study established an empirical basis for defining energy consumption profiles for a mobile device connected to 3G and WLAN networks and traffic profiles for structured P2P overlay networks.

Next, the thesis proposed a set of models for distributing load in an energy-aware manner among mobile devices so that energy-critical nodes would carry less load than non-energy-critical nodes. The e-Aware model was proposed for estimating the energy consumption of a mobile device in different distributed application scenarios. It was empirically verified to achieve 3-21% error in comparison to real-life measurements. The model accelerates the development of energy-efficient networking solutions by reducing the need for time-consuming iterations between system development and evaluations with real-life networks and devices. The e-Mon model was proposed for the energy-aware load monitoring of peer nodes. The model facilitates the participation of battery-powered devices in P2P and other distributed networks by enabling energy-aware load balancing where energy-critical mobile nodes carry less load than non-energy-critical nodes. It was empirically demonstrated to improve the battery life of mobile peer nodes up to 470%. Finally, the ADHT concept of mobile agent based virtual peer load balancing was proposed for sharing the peer responsibilities between constrained-capacity mobile peer nodes in a subnet so that they can participate in a P2P overlay without compromising their battery life. The results indicate that ADHT has great potential to remove the super-peer overload problem while decreasing the average power consumption of nodes in a subnet.

Overall, the thesis gives valuable insight into implementing energy-efficient P2P systems in mobile environments. The results of the thesis help enabling energy-aware P2P networking in mobile environments, which in turn enables the broader use of P2P networking as a general-purpose optimization method in different computing systems, such as cloud computing. The thesis contributes to a topic of a growing importance, since a growing share of Internet nodes is mobile and it is foreseen that machine-to-machine device connections worldwide will grow rapidly during the coming years.

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