Consumer-Oriented Integration of Smart Homes and Smart Grids: A Case for Multicast-Enabled Home Gateways?

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***Abstract*—Smart Home automation is pushing into the consumer market for several years, while at the same time energy companies are working on the deployment of Smart Grids. Although, a key idea of the energy transition is to integrate small energy devices at the consumers site, the potential benefits of Smart Home technologies for Smart Grids remain unused at large until now. In this work we present a concept for consumer-oriented integration of Smart Home devices into Smart Grid applications using multicast-enabled Home Gateways. An evaluation using standard consumer hardware confirms general feasibility and performance of our approach. Further, we deployed a measurement testbed in the metropolitan area of Hamburg to analyze typical end-to-end Internet connectivity of consumer households.**

I. Introduction

Smart Home technologies have gained more and more attraction in the consumer electronics market for several years now. By offering services like automation of home-appliances (light, heating, ventilation), they increase comfort of household residents and can help to reduce energy consumption on a small scale. In a broader scope, the deployment of Smart Grids is foreseen to be a key element of the energy transition from fossil fuel to regenerative resources for the production of electricity.

Smart Grids enable coordination among devices to level supply and demand of energy, thereby keeping the power grid stable. For example, by adapting power consumption to available capacities, i.e., *Demand Side Management* (DSM). It was shown, that load shifting using DSM reduces peak energy demand by up to 17 % [1]. Load balancing also significantly decreases the average deviation from mean power. Long term evaluation [2] proposes a reduction of more than 20 %.

On the one hand, Smart Grids rely on the control of numerous small energy generators and consumers, that mainly reside at households. On the other, Smart Home technologies are already deployed in many households to control various (energy) appliances. Yet, there is no interconnection and integration of these two *Smart* domains, despite the obvious necessity and their potential benefits. This is a consequence of the two major challenges for Smart Grids; they require: (i) a communication infrastructure with access to a large number of households, and (ii) coordination and control of energy devices. Both should be efficient and scalable – without raising high costs.

In this paper, we contribute a concept for consumer-oriented, cost-efficient connection of households over public networks, i.e., the Internet, using multicast-enabled Home Gateways. Our approach is based on an embedded version of the H∀Mcast architecture [3] for hybrid multicast. Further, we present results from a performance evaluation on standard consumer hardware and report on a measurement study for Internet connectivity at consumer households.

The remainder of this paper is organized as follows. In section II we outline our concept of multicast-enabled home gateways. Afterwards (§ III) we discuss deployment considerations of our approach for future Smart Grid infrastructures. In section IV we present the results of the performance evaluation and our measurement study. We conclude in § V and give an outlook on future work.

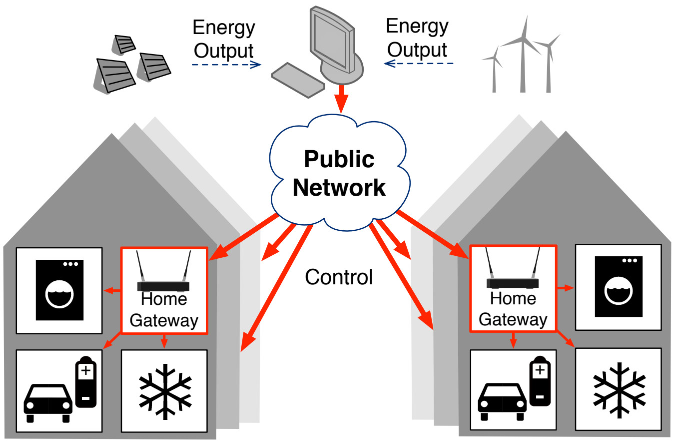


Fig. 1. Home-Gateways as representative of a Smart Home domain.

II. Multicast-Enabled Home Gateways

Future households in the Smart Grid will have more than the classical role as consumer of electricity. They will be deeply embedded into the entire process of electricity production, storage and consumption. For example, energy devices at the consumer side will be part of *Advanced Metering Infrastructures* (AMIs), *Demand Side Management* (DSM), and *Virtual Power Plants* (VPPs). These Smart Grid applications require a huge amount of processing and machine-to-machine communication, and therefore adequate access to many energy devices of a household. The deployment of a dedicated Smart Grid communication infrastructure to fulfill these tasks would be rather expensive.

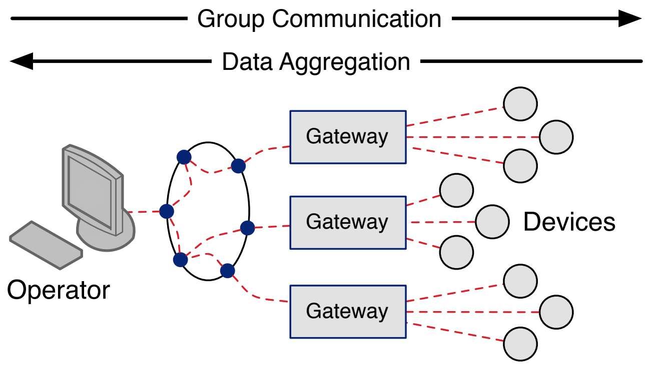


Fig. 2. Advanced Metering Infrastructure (AMI) realized using multicast communication with data aggregation of the reverse channel at the gateways.

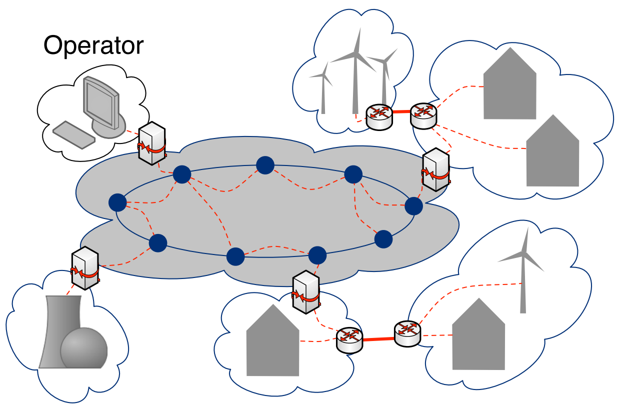


Fig. 3. Smart Grid communication infrastructure using hybrid multicast.

However, today most consumers have an Internet connection in their household that is maintained by a dedicated hardware box – e.g., a WLAN Router or *Home Gateway*. Typically a Home Gateway provides Internet connectivity for devices in a household and has enough resources left to host additional services, e.g., media storage or network printing. Thus, a Home Gateway is perfectly suitable to be enhanced with software for Smart Grid applications (s. Fig. 1).

The communication patterns of AMI, DSM, and VPP can be summarized as *one-to-many* and *many-to-many* among a group of devices. Such group communication is best implemented by multicast, which provides scalable and efficient real time transmission to a group of receivers. In contrast, unicast communication has several drawbacks: (a) an operator has to maintain a list of households, to which (b) data is separately send. We argue in favor of (hybrid) multicast over public networks, that unburdens operators from managing a dedicated connection to each household (or device). Multicast distributes load from sender into the network by originating data only once and duplicating it within the network.

In our concept the Home Gateway is a representative of a consumer household that receives and propagates information. Using multicast, Home Gateways can coordinate tasks among energy devices very efficiently, e.g., for DSM or VPPs [4]. For services requiring feedback, information can be aggregated by gateways along the reverse channel (see Fig. 2). This requires software on Home Gateways that enables data aggregation and encryption mechanisms for reverse multicast traffic [5], e.g., for AMI.

III. Deployment Considerations for a Future Smart Grid Infrastructure

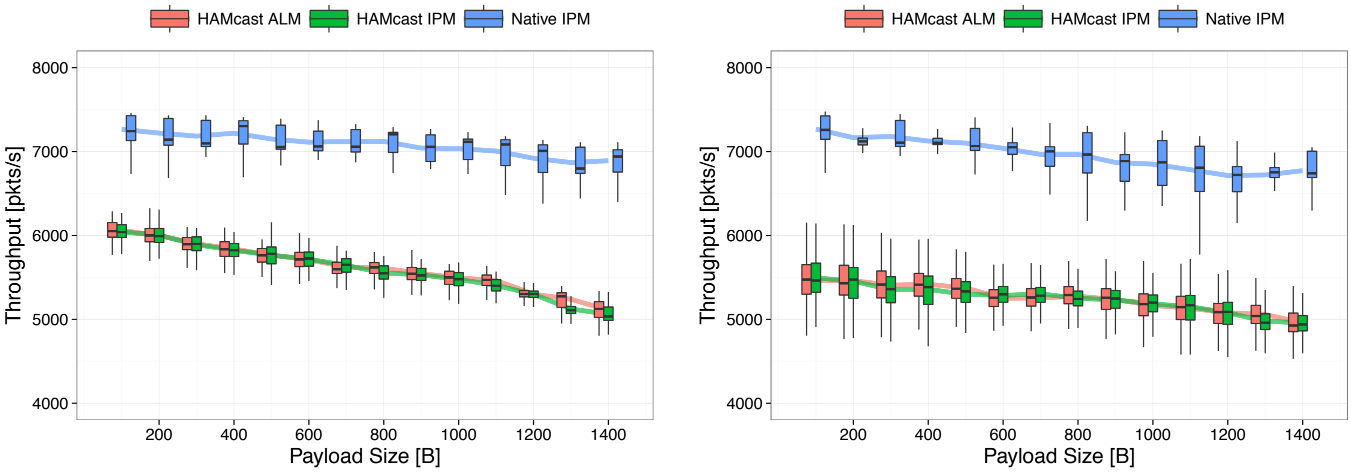
Our concept of multicast-enabled Home Gateways relies on the general availability of a group communication service in public networks, i.e. the Internet. Unfortunately, IP multicast is not commonly available throughout the Internet due to its deployment complexity. With the emergence of peer-to-peer overlay networks, p2p concepts were also adopted to implement group communication: application layer multicast (ALM). The general idea behind hybrid multicast is the integration of different group communication schemes to overcome distinct technology dependent problems. Most hybrid multicast approaches combine the efficiency of IP multicast and straightforward deployment of overlay schemes.

To enable multicast between Home Gateways, we use the H∀Mcast architecture [3] for hybrid multicast. The hybrid approach of H∀Mcast transparently integrates heterogenous multicast technology to enable universal group communication over the Internet. Figure 3 shows Smart Grid infrastructure using a hybrid multicast network spanning heterogenous multicast domains, i.e., IP multicast edge networks inter connected by an overlay multicast.

The H∀Mcast concept consists of a common multicast API [6] with an abstract naming scheme for multicast groups, combined with an adaptive middleware layer. H∀Mcast abstracts from underlying multicast technologies and solves the problem of missing standards for application layer multicast (ALM) schemes by defining a technology independent communication interface. Existing administrative and technological borders are transparently bridged using *Inter-domain Multicast Gateways* (IMGs).

Data security and integrity as well as privacy are very important aspects for Smart Grid applications. Multicast communication already provides a certain degree of implicit privacy by decoupling sender and receiver, that is the sender does not know all (if any) receivers. Moreover, group names (URIs) as defined by the H∀Mcast API can include security credentials to enable authentication of multicast sender and listener. Further security features can be implemented on other network layers or by the Smart Grid application.

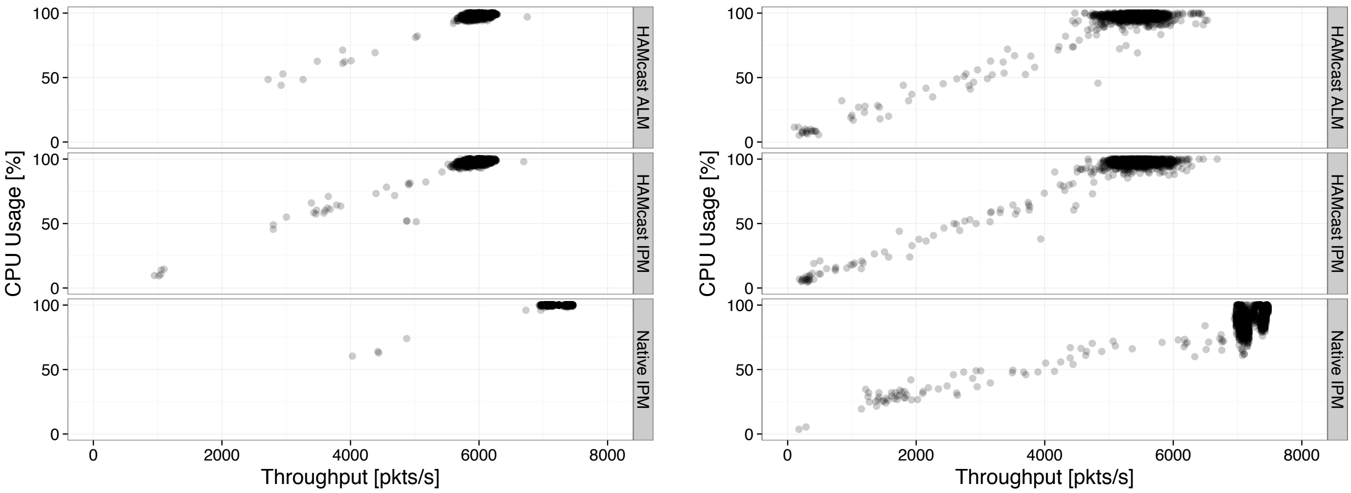
Another issue is the integration of legacy hardware and systems. Home Gateways based on standard consumer hardware, provide multiple IO interfaces (Wifi, USB, Bluetooth, DECT) to connect various Smart Home devices. They can also be enhanced with specific adapters to support widely deployed protocols such as ModBus-TCP and IEC60870 or even new standard protocols like IEC61850. Thus, Home Gateways enable incremental deployment by flexibly integrating (legacy) Smart Home appliances into Smart Grid applications.



(a) Sender

(b) Receiver

Fig. 4. Comparison of packet throughput vs. payload size for Native IPM, H∀Mcast IPM and ALM on sender and receiver side.



(a) Sender

(b) Receiver

Fig. 5. Comparison of CPU usage vs. packet throughput for Native IPM, H∀Mcast IPM and ALM on sender and receiver side.

IV. Performance Evaluation and Measurement Study

For deployment and evaluation of our approach, we adapted the H∀Mcast implementation to run on embedded devices where resources such as CPU and memory are rather limited. Specifically, we ported H∀Mcast on an off-the-shelf WLAN router with an ARM processor @400 MHz and 32 MB RAM running OpenWRT (s. http://openwrt.org). This device provides a typical platform for Home Gateways at consumer households. Our analysis is divided in two parts: First, we evaluate system performance of H∀Mcast on Home Gateways, and second, we deployed a testbed in the metropolitan area of Hamburg to study Internet connectivity of consumer households measuring one-way message delays.

A. H∀Mcast *on Home-Gateways*

The test setup to evaluate the raw system performance of H∀Mcast consisted of two Home Gateways directly connected via their internal 100 MBit/s Ethernet switch ports. Both nodes running a benchmark tool that measures packet throughput and loss as well as CPU utilization at sender and receiver. Besides native IP multicast (Native IPM) as reference technology, we evaluated H∀Mcast using IP multicast (HAMcast IPM) and H∀Mcast using application layer multicast (HAMcast ALM) based on Scribe. We tested payloads ranging from 100 Bytes (B) to 1400 B with steps of 100 B. Packets were sent with an interval of 1 s. For each technology and payload size we conducted 15 experiments with a runtime of 60 s each, in an alternating order. We discarded 3 s at the beginning of each run to allow the system to stabilize (build-up phase).

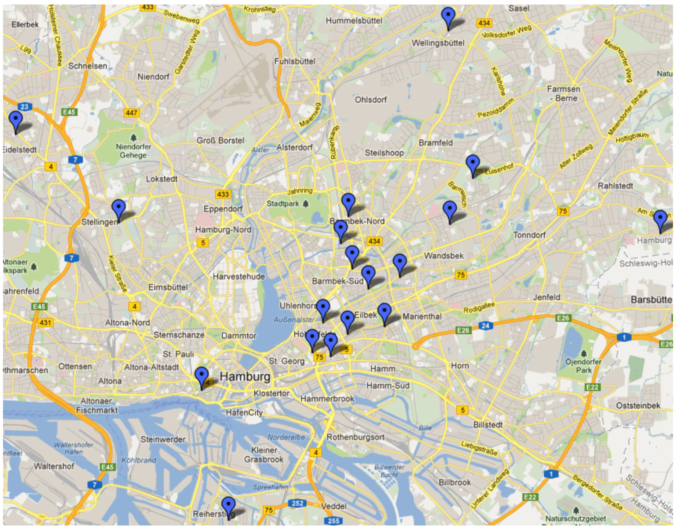


Fig. 6. Measurement probes deployed in Hamburg.

Figure 4 shows the results for packet throughput over varying payloads at the sender (a) and receiver (b). As expected, packet throughput decreases with increasing payload size for all schemes. However, the bottleneck is not network bandwidth but rather CPU resources, as shown below. Native IPM has an average throughput of 7000 packets/s over all payload sizes, while H∀Mcast IPM and ALM achieve a throughput of 5500 packets/s on average, that is $\approx$ 80 % of native IPM. Surprisingly, even Native IPM cannot fully utilize the available network bandwidth of 100 MBit/s with a payload of 1400 Bytes, which would correspond to a maximum throughput of $\approx$ 8700 packets/s.

We also analyzed resource consumption in terms of CPU usage during send and receive operation. Figure 5 shows the comparison of packet throughput and CPU usage for Native IPM, H∀Mcast IPM and ALM. For all schemes, CPU usage is close to 100 % for the sender and receiver. As expected, the results indicate a direct and proportional relation between CPU usage and achieved throughput. This again shows the constraints of hardware resources on standard consumer platforms. However, the achieved packet throughput is more than sufficient for Smart Grid applications.

B. Distributed Measurement

To analyze performance impacts and characteristics of Internet access connections at consumer households, we deployed a measurement testbed of 30 nodes connected via 9 different Internet service providers (ISPs) in the metropolitan area of Hamburg, Germany (see Fig. 6). In first experiments, we measured one-way message delays using the framework and methodology described in [7].

Figure 7 shows the results comparing one-way message delays from measurements in the Hamburg testbed with our previous findings from large-scale measurements in national (Germany) and continental (Europe) setups using the Planet-Lab Europe testbed [4]. In all scenarios (Hamburg, Germany, Europe) the sender was located at our university (HAW Hamburg) and transmitted packets of 1000 Bytes payload with an interval of 1 s to all receiving nodes. It is worth mentioning, that most Planet-Lab nodes are located at universities and research institutes, consequently most of them have Internet access with high bandwidths, low latencies and overall good connectivity. Contrary to consumer households, where these characteristics are very diverse and differ between ISPs (see below Fig. 8).

The boxplot in Fig. 7(a) reveals that average one-way message delays in the Hamburg testbed are of the same magnitude as in a European setup using the Planet-Lab testbed. Which is surprisingly high considering the limited, regional testbed expansion. However, as shown in histogram Fig. 7(b) delay deviation in the European Scenario is higher due to topological and geographical distance between sender and receivers.

We also analyzed the relation of one-way message delays and ISP association of consumer households. Therefore, we measured delays between all nodes within the Hamburg testbed over a period of 24 h. As before, each sending Home Gateway transmitted packets with a payload of 1000 Bytes and with an interval of 1 s to all other nodes. Figure 8 shows the results from a sender (a) and receiver (b) point of view. Most ISPs exhibit larger delays on the sender side, which likely corresponds to asymmetric upstream and downstream of most consumer Internet connections. Moreover, receiving delays are widely distributed compared to the sender side.

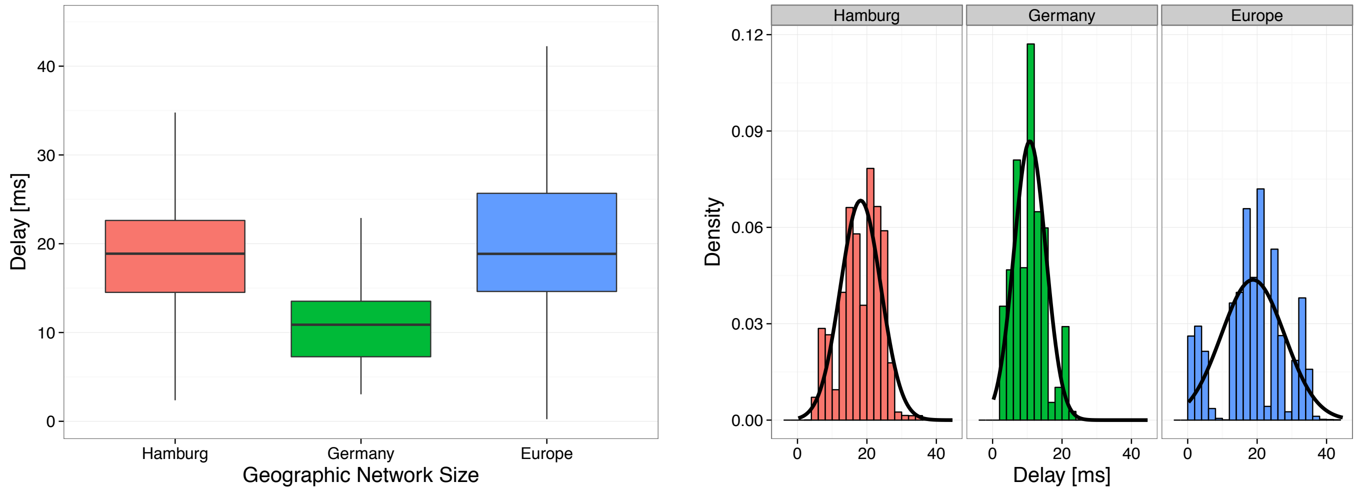
V. Conclusion and Outlook

Smart Grids require a communication infrastructure that enables scalable and efficient machine-to-machine communication among numerous energy devices at the consumer site (households) without raising high costs. In this work we outlined a consumer-oriented concept to integrate Smart Homes and Smart Grids via multicast-enabled Home Gateways over the Internet.

Our approach uses the H∀Mcast architecture for hybrid multicast, that we adapted to run on embedded standard hardware, i.e., Home Gateways. The results of our performance evaluation show high packet throughput rates over varying payload sizes that are more than sufficient for Smart Grid applications such as AMI, DSM, and VPP.

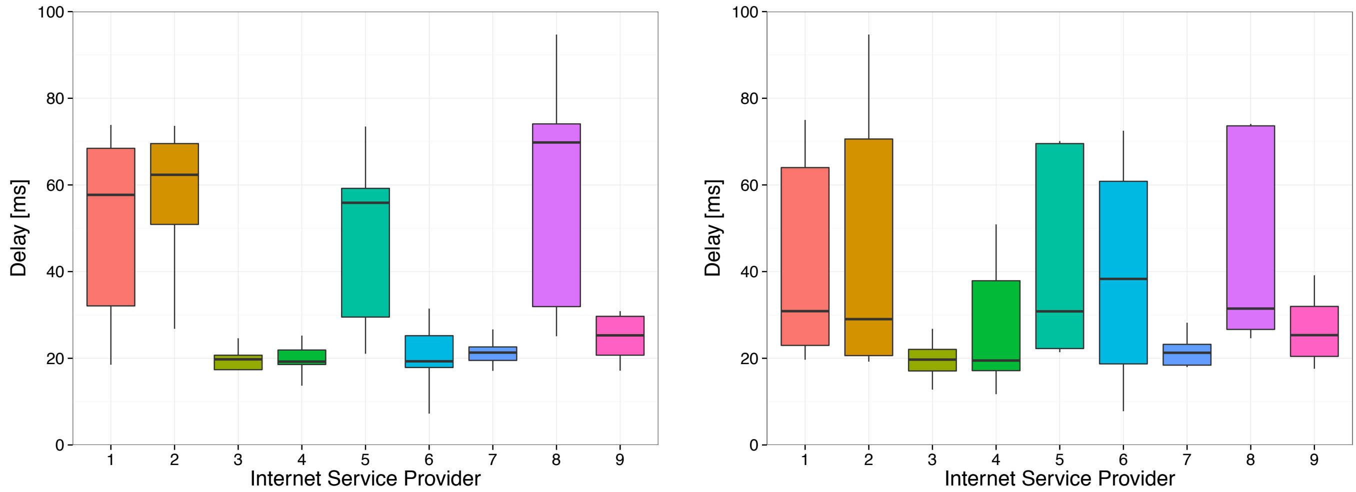
Further, we deployed a realistic Smart Grid testbed of Home Gateways at consumer households in the metropolitan area of Hamburg. In a first analysis we measured one-way message delays to evaluate characteristics of consumer Internet connectivity. We found that delays are surprisingly high for such a regionally confined scenario. Moreover delays heavily depend on provider association and differ considerably between ISPs.

In our ongoing research we focus on measurements and experiments in our Hamburg testbed for further analysis on the impacts of consumer Internet connectivity on (future) Smart Grid applications. We are also working on decentralized coordination schemes for energy devices that utilize our concept of a multicast-enabled Smart Grid communication infrastructure.



(a) Boxplot (b) Histogram

Fig. 7. Comparison of one-way message delays for different network sizes by geographical expansion.



(a) Sending (b) Receiving

Fig. 8. Comparison of sending and receiving one-way message delays for different Internet service providers.

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