A Scalable Communication Infrastructure for Smart Grid Applications using Multicast over Public Networks

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ABSTRACT

The transition to regenerative energy resources paves the path from a small number of large power plants to a grid of highly distributed, heterogeneous small generators. To establish a Smart Grid it requires a scalable machine-to-machine communication that allows to control and coordinate millions of energy producing and consuming devices. In this work we contribute a future deployment concept of a scalable communication infrastructure for Smart Grids. Our proposal is based on group communication utilizing hybrid multicast over public networks. We show by real-world measurements that our approach achieves high scalability while also limiting end-to-end communication delay.

Categories and Subject Descriptors

C.2.4 [**Computer Networks**]: Distributed Systems

Keywords

smart grid, multicast, network infrastructure, evaluation

1. INTRODUCTION

A scalable communication infrastructure for power grids that can handle millions of heterogeneous devices is a necessity for the energy transition from fossil fuels to regenerative resources. Future Smart Grids shall enable the intelligent management of numerous highly distributed energy producers and consumers in diverse applications. For example, a *Virtual Power Plant* (VPP) connects small power generators such as cogeneration, wind power or photovoltaic plants that adapt to the current demand. At the same time the customers energy consumption is metered and, where appropriate, leveled or optimized to the current load of the power grid by dynamically turning devices on and off. Metering (AMI) and *Demand Side Management* (DSM) are mandatory as regenerative power generation underlies variabilities due to continuously changing environmental conditions, but they also allow to smoothen peak loads.

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However, AMI and DSM as well as VPP are communication-centric applications that require a scalable network infrastructure. They offer new business opportunities for established energy companies, but also imply heavy investments in communication networks for energy devices. The communication costs in Smart Grids can be significantly reduced by utilizing public networks, such as the Internet, thereby also attracting companies that have no tradition in the energy market. For example, Internet Service Providers (ISPs) already have access to a large number of households.

In this paper, we contribute a concept of a communication infrastructure for future Smart Grids that is scalable, efficient and has minimal configuration costs. The deployment model for our approach is based on hybrid adaptive multicast over public networks and provides intermediate gateways in the infrastructure. These nodes allow to host components and functionality to support Smart Grid applications. We apply our approach on *Advanced Metering Infrastructures* (AMI), DSM, as well as VPP scenarios, and discuss its benefits over traditional unicast Smart Grid communication. We evaluate our approach by real-world measurements in national and continental setups on Planet-Lab and G-Lab. The results show that multicast-based Smart Grid communication offers a significant gain in scalability, while keeping latency within desired bounds.

The remainder of the paper is organized as follows: In Section 2 we outline challenges for Smart Grid deployments that motivated our approach and survey related work. The concept for scalable smart grid communication and its application is introduced in Section 3. In Section 4 we present and discuss the results of our evaluation. We conclude in Section 5 and give an outlook on future work.

2. CHALLENGES & RELATED WORK

Demand Side Management enables active control of energy consumption. Even though installations today are rare and mostly cover large scale consumers, DSM can also be forseen in households. Decentralized DSM offers significant benefits for grid operators and consumers of electricity. It allows to efficiently utilize the available capacity of the power grid by enabling dynamic pricing models to offer incentives for consumers. Empirical evaluations [7] of smart home installations show that by shifting loads, the peak demand can be reduced up to 17 percent. But a widely deployed cooperative DSM application also implies many signals from the grid operator to millions of consuming devices – thus requiring a scalable communication infrastructure.

To compensate fluctuations in the power grid, control energy must be hold ready. Positive control energy is used when more energy is consumed than predicted and negative control energy is used when supply exceeds the estimated demand. To trade at the energy market a provider must offer a certain minimum capacity. This locks out most of the regenerative energy sources. A Virtual Power Plant is a cooperatively organized set of distributed small power generators, that in sum achieves the required capacity. Schulz et al. [9] propose an architecture and communication concept for a VPP based on electrical vehicles.

Another key application is an Advanced Metering Infrastructure that scales to the large number of smart meters. These require a two way communication between energy supplier and consumer to periodically exchange billing and price information and report back on energy consumption. Zhao Li et al. [3] introduce an abstraction layer for smart metering to integrate various AMI systems into a single distributed management application.

In summary, these applications demand for a highly scalable and efficient machine-to-machine communication to accommodate for thousands or even millions of devices. Further features, such as decoupling of sender and receiver, zero configuration, or transparent transport are a necessity in Smart Grids to keep the system manageable. Baker et al. [1] outline the key infrastructure protocols of the Internet protocol suite for use in the Smart Grid. The authors argue in favor of multicast, but they do not address the deployment complexity of multicast forwarding between ISPs.

3. SCALABLE COMMUNICATION IN THE SMART GRID

A Smart Grid is a highly distributed system that uses machine-to-machine communication to connect heterogeneous endsystems to cooperatively execute a task or establish a unified view on the system state. Our concept is based on the observation that the underlying communication patterns can be summarized as *one-to-many* and *many-to-many*. Due to this group communication we argue in favor of multicast, which is a common method to overcome issues of scalability when information is transferred simultaneously to a group of receivers. Assuming N devices, a unicast based solution as commonly used today has several drawbacks: (a) the sender (operator) has to know and maintain a list of all devices, and (b) one request or update message causes N consecutive send operations. In contrast, multicast messages are sent only once by the source and are duplicated within the network to reach all receivers. This distributes the load from sender to network and reduces bandwidth usage. Multicast communication also unburdens the sender from managing a dedicated connection to each receiver.

3.1 The Multicast Enabled Smart Grid

A typical Smart Grid scenario is dynamic pricing in AMI, where smart meters receive periodic updates on the energy tariff. This is a common implementation of the one-to-many pattern. Very similar, in DSM or VPP use cases an operator has to send control, update, and request messages to numerous devices. Furthermore, to support decentralized coordination and propagate state updates to achieve a consistent view, energy devices can utilize many-to-many communication within their group.

The assignment of energy devices to distinct multicast groups is important to achieve scalability and efficient control in Smart Grid applications. For instance in AMI, groups

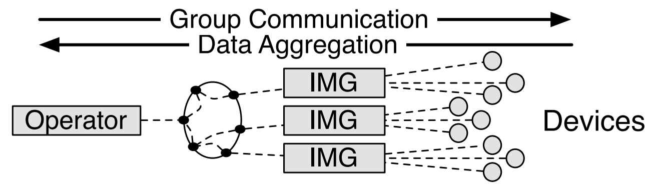

Figure 1: Advanced Metering Infrastructure (AMI) realized using multicast communication with data aggregation of the reverse channel at the IMGs

of smart meters with the same dynamic pricing model (e.g. Real-Time, Critical Peak) enable efficient distribution of tariff information among the endsystems. For VPPs, groups can cover geographical regions, as well as different classes of power sources, thereby allowing to adapt to the regional energy demand or environmental conditions. For the same reason, homogeneous consumers and devices in a single accounting grid can be grouped together in the DSM scenario. Group affiliation is configured during deployment of a device and requires no configuration at the operator side.

3.2 Deployment Considerations

IP multicast [2] is not commonly available throughout the Internet because of its deployment complexity. The idea of hybrid multicast is the integration of different group communication schemes to overcome the distinct technology dependent problems. Thus, hybrid multicast approaches can combine efficiency of IP multicast and straightforward deployment of overlay schemes. We proposed H∀Mcast [4], an evolutionary system architecture to enable a universal multicast service. The concept consists of a common multicast API [10] with an abstract naming scheme for multicast groups, combined with an adaptive system middleware and transparent *Inter-domain Multicast Gateways* (IMGs) to overcome existing administrative and technological borders. H∀Mcast abstracts from underlying multicast technologies and solves the problem of missing ALM standards by defining a technology independant communication interface. In this work, we use a public-domain implementation of the H∀Mcast architecture.

In our proposal, the home or regional provider networks use native IP multicast, while the borders of these IP multicast domains are traversed using overlay multicast. Home or provider gateways can host functionality, such as leveling applications, to control and coordinate energy devices. The gateways also act as representatives that receive and propagate information to energy devices within their domain. This reduces the load at the operators side and uses the effects of physical proximity on the communication latency. For services that require feedback or acknowledgments, the benefit of multicast at the sender side is normally low, as the responses cause high load. To reduce the load, the answers related to such requests can be aggregated and preprocessed at the home or provider gateways (IMGs) in the network (see Fig. 1). This requires a specialized software to be deployed with the IMG that enables security and data aggregation for reverse traffic [6].

Our deployment concept can also support legacy applications and protocols by tunneling or encapsulation, as proposed by Sauter et al. [8] for their unicast-based architecture. This enables an evolution of the Power Grid by maintaining compatibility to established protocols during migration.

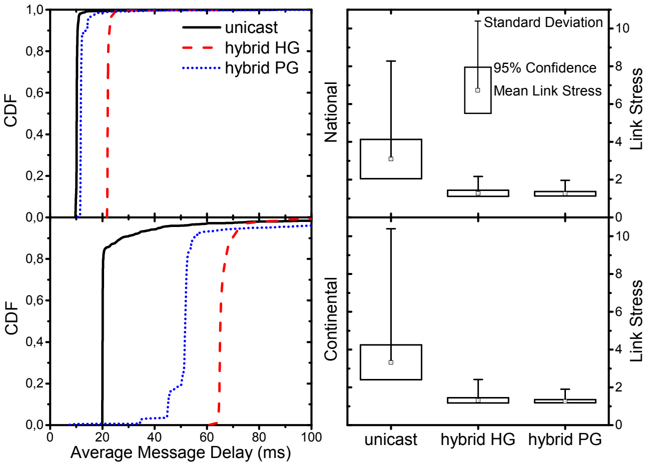

Figure 2: Analysis of average message delay and link stress in national (DE) and continental (EU) setups.

4. MEASUREMENT RESULTS

To analyze the scaling behavior of group communication schemes in Smart Grids we evaluated national (German, DE) and continental (European, EU) scenarios in our measurements. The setups correspond to realistic Smart Grid deployments in the near future. For our measurements we used the H∀Mcast implementation (`hamcast.realmv6.org`) and deployed it on the Planet-Lab Europe and German-Lab testbeds. For the national setup we used 30 nodes from 15 different sites in Germany and for the continental 60 nodes at 30 European sites. We analyzed one-way message delay and link stress between source and all receiving nodes [5]. For each experiment, we sent packets of 1000 bytes payload within an interval of 1 s using three distinct group communication schemes: n-times unicast, hybrid multicast with home gateways (hybrid HG) and hybrid multicast with provider gateways (hybrid PG).

In Figure 2 we show the results of our real-world measurements. As expected, message delays (Fig. 2, left) are lowest for n-times unicast, while hybrid multicast adds an extra delay of 10 ms for the national and 40 ms for the continental setup. The extra delay is caused by the overlay multicast scheme as well as the structure and depth of multicast distribution trees. Compared to the inertia of common energy devices in the range of seconds to minutes, the observed delays remain small in orders of magnitude for all schemes.

Further, network resources (such as bandwidth) are limited and thus scaling behavior is also influenced by the load induced when sending (control) messages to devices in a Smart Grid. We therefore compared link stress of n-times unicast and hybrid multicast schemes (Fig. 2, right). The graphs present an analysis of the mean link stress as well as the 95 % confidence interval (box), and standard deviation (error bar). As our findings show, overall link stress of n-times unicast is significantly higher than for hybrid multicast. In all scenarios, n-times unicast exhibits a mean link stress of nearly 3 with high standard deviations of 5 (DE) and 7 (EU). While both hybrid multicast schemes have mean link stress of 1.3 with standard deviations close to 1. The maximum link stress of unicast corresponds to the number of group members. Thus, link stress indicates potential network bottlenecks that affect the overall scaling behavior of Smart Grid communication.

5. CONCLUSION & OUTLOOK

In this work, we introduced a deployment model for future Smart Grids that enables scalable and efficient communication over public networks. We identified common communication patterns of Smart Grid applications, i.e. one-to-many and many-to-many, and showed how these patterns can benefit from our proposed concept. Further we evaluated the communication concept using real-world measurements of one-way delays and bandwidth utilization (link stress) in a national (German) and continental (European) setup. Our results show a significant advantage in bandwidth utilization when using hybrid multicast. In our ongoing work, we will concentrate on simulation to evaluate and fine-tune our approach. We also work on a prototype implementation for real-world deployment on embedded devices.

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