A Scalable Communication Architecture for Advanced Metering Infrastructure

Giang Ngo Hoang, Luigi Liquori, Hung Nguyen Chan

A Scalable Communication Architecture for Advanced Metering Infrastructure

Giang Ngo Hoang*†§, Luigi Liquori*, and Hung Nguyen Chan¶
*National Institute for Research in Computer Science and Control, France, Email: [name.surname]@inria.fr
†Université de Nice Sophia-Antipolis, France
§Hanoi University of Science and Technology, Vietnam
¶Vietnam Research Institute of Electronics, Informatics and Automation, Vietnam, Email: hungnc@vielina.com

***Abstract*—Advanced Metering Infrastructure (AMI), seen as foundation for overall grid modernization, is an integration of many technologies that provides an intelligent connection between consumers and system operators [ami 2008]. One of the biggest challenge that AMI faces is to scalable collect and manage a huge amount of data from a large number of customers. In our paper, we address this challenge by introducing a mixed peer-to-peer (P2P) and client-server communication architecture for AMI in which metering data is aggregated and processed distributedly at multiple levels and in a tree-like manner. Through analysis we show that the architecture is featured with load scalability, resiliency with failure and partly self-organization. The experiments performed in large scale French Grid5000 platform [G5k] shows the communication efficiency in the proposed architecture.**

Keywords. Peer-to-Peer, Advanced Metering Infrastructure, Communication Architecture, Inter-connecting Overlays.

I. Introduction

In AMI system, smart meters measure and collect the energy consumption information, power quality from customers' premises. The metering data is, on-scheduled or on-demand, sent to *Metering Data Management System* (MDMS) which is a database with analytical tools allowing the interaction with system side applications such as *Consumer Information System* (CIS), *Outage Management System* (OMS), *Enterprise Resource Planning* (ERP). MDMS performs the validation, editting and estimation on the data and feeds the appropriate data to the system side applications to help optimize operations, economics and consumer service [ami 2008].

By current standards, a few kilobytes of data is collected from each smart meter every 15 minutes [Bernaudo et al 2010]. In addition, meter data can be collected on demand for billing inquiries, outage extent verification, and verification of restoration [Khan et al 2013]. When the scale of system is up to large, many existing communication architectures are not sufficient enough to deal with the waves of meter data due to the limitation in bandwidth.

In this paper, we address above challenge by introducing a mix P2P and client-server communication architecture that allows scalable data collection, aggregation and management. The proposed communication architecture comprises multiple points of data collection and processing, i.e. MDMS, which are geographically distributed and hierarchically organized. The metering data is collected, then is aggregated and transferred through multiple levels of MDMS in a tree manner thus reduce the throughput of data after each level. While the MDMSs are organized in a P2P architecture to take the self-organization, scalability and resilience advantages of P2P, the connection from the MDMSs to smart meters following the client-server model as normally to be compatible with different kind of collectors and smart meters. As such, the main contribution of this paper is the introduction of a new communication architecture for AMI featured by characteristics including scalability, resilience and partly self-organiation.

Our paper is organized as follows. Section II introduces the related work and our focus. In Section III, we describe the proposed communication architecture and investigate its characteristics. The communication infrastructure is evaluated by experiments on large scale platform Grid5000 [G5k] in Section IV. Finally, we draw conclusions and introduce the future work in the Section V.

II. Related work and our focus

Several communication architectures for AMI have been proposed in the last few years.

The traditional communication architecture [ami 2008] being one central *Operation Center* (OC) receiving metering data from all customers through local data concentrators. With this centralized architecture, all metering data go through the MDMS at OC which then feeds the appropriate data into system side applications. This architecture makes the system simple and easy to manage. However, as the scale of system ups to large, this architecture is suffered from several non-scalable problems. First is the high possibility to create the bottlenecks in data communication in the zones close to the OC as pointed out by Author in [Jiazh et al 2012]. Second is the unfeasibility in data processing due to the large data load, pointed out by Author in [Gerdes et al 2009].

The Author in [Jiazh et al 2012] introduced a model with some similarities with *Content Delivery Network* (CDN) [CDN] in which a central MDMS connects to multiple distributed MDMSs. They introduced an algorithm to calculate the optimal deployment of distributed MDMSs in their model. The distributed architecture allows the aggregation of data thus solves the problem of non scalability in data collection.

The Author in [Meili et al 2013] proposed an infrastructure based on group communication using hybrid adaptive multicast over public networks. By relying on group communication over public networks, this approach reduces the cost of investment but the reliability of communication as well as the latency of data collection are not guaranteed.

The Author in [Arena et al 2010] investigate the storage and monthly billing processing architecture. They compared storage techniques including the centralized relational database, the distributed relational database and the key-value distributed database storage. Their work focuses on achieving the scalability in processing metering data rather than achieving the scalability in collecting the metering data.

The Author in [Rusitschka et al 2010] proposed a model of using cloud computing for smart grid data management. The advantages of computing are the ability to provide huge storage, powerful processing and communication. In this paper, while focusing on providing sufficient resources for smart grid data management, they do not investigate the distribution of necessary resources, i.e. points of data collection and management.

In our work, we focus on introducing a communication architecture for scalable data collection and management. Author in [Jiazh et al 2012] also proposed a communication architecture for scalable data collection using a CDN like model for MDMS network. In our work, we connect MDMS by a P2P network which is more resillient with failure than the model in [Jiazh et al 2012]. The scope of our work does not cover the investigation of data processing and integration algorithms.

III. AMI ARCHITECTURE

A. Structure

Figure 1 illustrates the proposed AMI communication architecture. The AMI comprises multiple OCs which are geographically distributed and hierarchically organized. Each OC contains a MDMS for collecting and analyzing metering data from customers belonging to the area that the OC is responsible for. The MDMS are equipped with analytical tools to interact with system-side applications which locate in that OC. As each OC has one MDMS, we use a cube to present both an OC and the perspective MDMS.

The level-1 MDMS is responsible for whole area where AMI covers. The whole area is divided into multiple sub-areas that each of which is covered by a level-2 MDMS. An area covered by a level-2 MDMS can be further divided into multiple sub-areas that each of which is covered by a level-3 MDMS and so on. The level-n MDMS managing area S_n and the level-$(n+1)$ MDMS managing area S_{n+1} such that $S_{n+1} \subset S_n$ are called parent and child of each other respectively.

All MDMSs are connected in P2P architecture as following. All children of a level-n MDMS with $n \geq 1$ are organized in a DHT overlay. The MDMS at level-n keeps contact of all of its MDMS children at level-$(n+1)$ while a MDMS at level-$(n+1)$ maintains the contact of its parent and contact of parent's neighbors in the parent's overlay. In case that the parent MDMS is at level-1, its children maintain

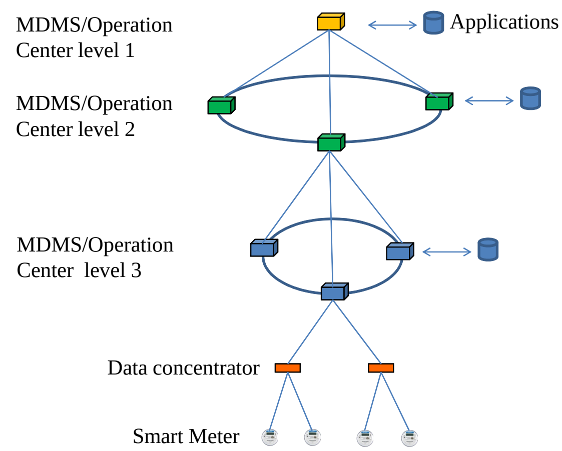

Figure 1: AMI proposed architecture

the contact of parent only. When the parent of a MDMS fails, the MDMS replaces its parent by the closest neighbor of the parent. If the old parent recovers from failure, the MDMS automatically changes the parent back to the old one. A MDMS also periodically check the aliveness of its children and remove the failed children from its children list.

Each MDMS at highest level manages a number of data concentrators following the client-server model. Each of the data concentrator collects metering data from a number of smart meters.

B. Data collection and processing

Upward direction: in this direction, customers on-scheduled or on-demand send metering data to local concentrators which then send the data to the MDMSs managing them. At each MDMS, the data is processed and aggregated and the appropriate data is fed to local system-side applications, only the summarized data is sent to parent MDMS and so on.

Downward direction: with downward direction, data and commands such as new energy price, request for reducing the load, from AMI applications in one OC can be send to customers through data concentrators. The MDMS at level-n can also send control commands or data to MDMSs at level-$(n+1)$. The schemes of communication include broadcast, multicast or unicast. A MDMS at level-n can send the data or command to all of its children MDMS or to a group of its children MDMS or to one of its children MDMS at level-$(n+1)$. A MDMS at highest level can send the data or command to all of its users or to a group of its users or even to a specific user.

System-side applications are deployed in OCs at appropriate levels depend on their functions, characteristics and requirements on latency. The applications that is sensitive with latency such as OMS, *Demand Response* (DR) should be deployed in OC at highest level, i.e. close to the smart meters, while other applications which are less sensitive with latency such as Billing system can be located in OC at lower level. The distribution of applications in high level OCs also help to reduce the throughput of data flowing toward the lower level OCs thus make the system more scalable in term of data communication.

MDMS and system-side applications such as CIS, OMS, GIS located in one OC can interact with each other in several patterns. MDMS can on-demand or on-scheduled feeds data to system-side applications. Other way of interaction exploits the Publish-Subscribe model in which these applications subscribe for certain kind of event such as the outage flags generated by AMI system so that these applications are notified when the events happen. To enable these interactions, the utility can deployed analytical tools or publish-subscribed applications a long with MDMS to provide the appropriate data to the applications.

C. System analysis

This section investigates the characteristics of our architecture including load scalability, resilience with failure. We also estimate the latency of gathering data in OCs at different levels. The parameters of the model are denoted as following:

- M: the number of smart meters in the system;
- L: the highest level of OCs;
- λ_i: the number of messages generated by a smart meter in a period of time;
- α_n: the load over a MDMS at level n, calculated by a number of messages go to this MDMS. The load over a MDMS shows two aspects: the throughput of data flowing to the OC and the power processing needed to process these messages.
- β_n: the number of messages that a MDMS at level $n+1$ sent to its parent MDMS at level n in a period of time;
- $z_n = \dfrac{\beta_{n+1}}{\beta_n}$ with $n = \overline{1, L{-}1}$.

In case $n{=}L$, we let z_L be the number of messages a data concentrator sent to MDMS managing it over the number of messages that it receives from smart meters.

- K_n: the number of MDMSs in all OCs at level n;
- $S = a^2$: the size of square area for which the AMI is responsible.

We note that $z_n << 1$ because the MDMS only sent summary data to its parent. This results in $K_n << K_{n-1}$.

Load scalability. According to [Scala], load scalability is the ability for a distributed system to easily expand and contract its resource pool to accommodate heavier or lighter loads or number of inputs. We define the load on AMI is the number of messages generated by all smart meters in one period of time which is calculated as following:

$$\sum_{i=1}^{M} \lambda_i = M \cdot \overline{\lambda}$$

with $\overline{\lambda}$ is the average traffic generated by a smart meter in a period of time. Thus the number of messages received by operation centers at level-n is:

$$M \cdot \overline{\lambda} \cdot \prod_{j=L}^{n} z_j$$

hence the load over a MDMS in level n is

$$\alpha_n = \frac{M \cdot \overline{\lambda} \cdot \prod_{j=L}^{n} z_j}{K_n} \tag{1}$$

with $n = \overline{1, L}$.

We note that in centralized model, the load on the central MDMS is:

$$M \cdot \overline{\lambda} \tag{2}$$

From Formula 1 and Formula 2, we can see following points:

Firstly, by distributing the MDMS and aggregating data at multiple levels, our model reduces the load on each OC comparing to the centralized model.

Secondly, by turning the number of aggregation levels and the number of OCs at each level, i.e. turning L and K_n, utility can control the load on each OC, i.e. control throughput and power processing requirement for each OC, thus eliminating the data transmission congestion as well as the overload in power processing. The adding or removing MDMSs to or from MDMS overlays can be achieved easily thanks to the self-management advantages of P2P. If the change of load happens in a local area, utility only need to adapt the number of MDMSs in the OCs which are responsible for that area. The easiness of changing the resource pool to adapt with either the global changes or the local changes of load shows the load scalability of AMI based on our architecture.

Failure resilience. The proposed communication architecture exploits the resilience with failure advantage of P2P in managing the MDMS network.

According to [Cascio], resilience means the capacity of a system to withstand sudden, unexpected failures, and (ideally) to be capable of recovering quickly afterwards. Resilience implies both strength and flexibility in the sense that a resilient structure would bend, but would be hard to break.

In our proposed architecture, the data of a MDMS can be replicated at its neighbors in the DHT overlay. As the MDMS fails, the closest neighbor automatically replaces it. On the other hand, a MDMS normally sends the data to its parent MDMS. In case the parent MDMS fails, the MDMS automatically send the data to the closest neighbor of the parent MDMS. Similarly, a data concentrator normally sends the data to its parent. In case the parent fails, it will send the data to closest neighbor of the parent. To deal with the situation that the level-1 OC fails, utility can deploy P2P applications for retrieving, querying data over overlay of MDMS at level-2.

As a matter of fact, even if the failure happen in some MDMSs, the system will quickly recovers and then works normally.

Low cost of maintenance and operation. With the large scale and the growth of AMI infrastructure, the self-organization ability of the MDMS network is very important in the sense that it helps the utility reduces the operation and maintenance cost. When the failures happen, the network automatically recovers without the human intervention. As the scale of system change, utility can easily add or remove MDMS with little early configuration.

Data gathering latency. One important task of AMI is to provide data with latency in the allowed limitation to smart grid applications. In this section, we estimate the latency of data gathering in OCs at different levels in which the smart grid applications can locate.

First we introduce some notation as following:

- T_n: is the latency for data, either metering data or summary data, to come to OCs at level n
- C_L: is the amount of time needed for transferring metering data from smart meters to a data concentrator and for processing the data in that data concentrator.
- C_n: is the amount of time needed for processing the data in an OC level n with $n = \overline{L-1, 1}$.

Then:

$$T_{n-1} = T_n + C_n + \Delta_T$$

with Δ_T is the time for transferring data from OC at level n to OC at level $n-1$. Assume that an OC is placed in the center of the area that it is responsible for. The OC level-n is responsible for the square area with the size:

$$\frac{a^2}{K_n}$$

The distance from OC level n to OC level $n-1$ is less than a half of diagonal line of above square area. Thus we have:

$$T_L < C_L + \frac{a}{\sqrt{2}} \cdot \sqrt{K_L} \tag{3}$$

and

$$T_{n-1} < T_n + C_n + \frac{a}{\sqrt{2}} \cdot \sqrt{K_n} \tag{4}$$

Formulas 3 and 4 show that our architecture allow to collect the data at various latencies. We can tune the L, and K_n parameters to have the latency for collecting data in OCs stay in the allow limitation.

IV. Evaluation of communication infrastructure

In this section, we evaluate the efficiency of the proposed communication architecture. To achieve this target, we implemented and evaluated the fundamental part of the communication architecture in which one MDMS overlay at level-n connects to multiple MDMS overlays at level-$(n+1)$. The other parts, namely the MDMS level-1 connect to overlay of level-2 MDMS and a MDMS connects to data concentrators in client-server architecture, are well investigated architectures. Therefore we did not implement and evaluate these parts.

A. *The implementation of communication architecture*

The implemented architecture is illustrated in Figure 2. In this implementation, Chord [Stoic et al 2001] overlay is used to connect MDMSs.

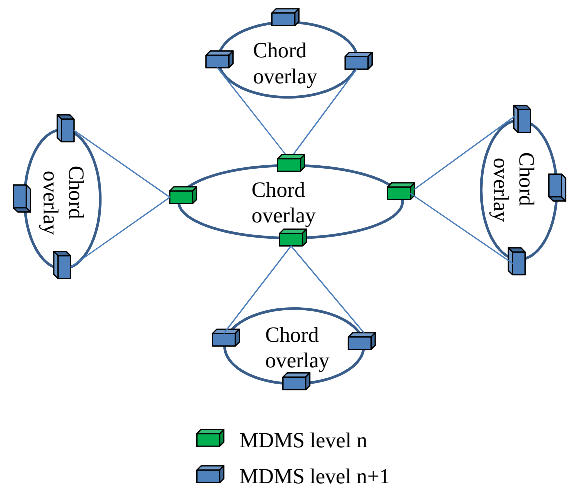

Figure 2: Evaluation communication architecture

1) ID assignment: We assign an unique p-bits identifier to each MDMS as following:

- The level-1 MDMS is assigned a random p-bits number.
- Each of the level-2 MDMSs is assigned a p-bits number in which q first bits is random and $p-q$ last bit is set to 0. Here $q << p$.
- Assume that a level-n MDMS with $n \geq 2$ has identifier with first $(n-1) \cdot q$ bits is m_0. Its MDMS children has identifiers specified as following: first $(n-1) \cdot q$ bits is m_0, next q bits is random and $p - n \cdot q$ last bits is set to 0.

2) Parent-children relationship: We hereby call a MDMS a peer for the sake of clarity.

Parent-children assignments.

A peer X is the child of a peer Y in the parent overlay if identifier of X stays between identifier of Y and identifier of Y's successor, i.e. the closest succeeding node of Y in the identifier space. Let X(Y) denotes X is child of Y. Assume that Z is successor of Y. $\mathtt{ID_X}$, $\mathtt{ID_Y}$ and $\mathtt{ID_Z}$ are identifiers of X, Y and Z respectively. Then we have that:

$$\mathtt{X(Y)}\ \textit{if}\ \mathtt{ID_X} \in [\mathtt{ID_Y}, \mathtt{ID_Z})$$

Children list and parent list. A peer maintains a children list and a parent list to keep the information of its children and parents. The children list of a peer contains information about all of its children. The parent list contains the information about the parent peer and parent peer's predecessor peers, i.e. the closest preceding peers of the peer in the Chord identifier space.

3) Communication schemes: Utility can employ various communication schemes for MDMSs to exchange data, command, information between each other. These schemes can be categorized into three categories based on the direction of the communication: intra-overlay communication, downward communication and upward communication.

Intra-overlay communication is the communication between MDMS in one Chord overlay. A MDMS can employs unicast, broadcast over DHT and multicast over DHT for intra-overlay communication. In this chapter, we called these schemes intra-unicast, intra-multicast and intra-broadcast to distinguish them with similar schemes in downward communication.

Many studies such as [El-Ans et al 2003], [Castro et al 2006] proposed algorithms for broadcast over a DHT. In our implementation, we used the broadcast algorithm proposed by [El-Ans et al 2003] as intra-broadcast while the intra-multicast algorithm is adopted from [El-Ans et al 2003] by ourselves.

Downward communication is the communication from parent MDMS to children MDMS. A MDMS can use any of the three schemes: downward-unicast, downward-multicast and downward-broadcast to respectively send information, i.e. data or commands, to its specific child MDMS or to a group of its children MDMSs or to all of its children MDMSs.

Upward communication is the communication from a MDMS to its parent MDMS. A MDMS use upward-unicast to send information to its parent MDMS.

Combination scheme. The combination between intra-overlay communication and downward communication allows the utility to unicast, multicast or broadcast information, i.e. data or command, to a specific MDMS, a group of MDMS or to all MDMS in any area.

The idea of combination scheme is as following. The sending MDMS first employs intra-unicast or intra-multicast or intra-broadcast to send the information to a specific MDMS or to a group of MDMS or to all MDMS in the same overlay with it. The receiving MDMS then forwards the information to one of its children or to group of its children or to all of its children.

The combination scheme constitutes three kind of communication as following:

- Combination-unicast: used by a MDMS at level n to send information of a specific MDMS at level-$(n+1)$
- Combination-multicast: used by a MDMS at level n to send information of a group of MDMS at level-$(n+1)$
- Combination-multicast: used by a MDMS at level n to send information of all MDMS at level-$(n+1)$

B. Evaluation

1) Objectives: This section evaluates two characteristics of our P2P architecture under various churn conditions, i.e. the join and leave of MDMSs. First is the efficiency of communication schemes in term of the ratio of successful communication. Second is the traffic for maintenance the network of MDMSs in a period of time characterized by the amount of traffic generated by a MDMS

The intra-overlay communication was evaluated in many previous papers such as [Stoic et al 2001], [El-Ans et al 2003]. Therefore we focus on evaluating the efficiency of combination scheme and upward communication including: combination-unicast, combination-multicast and upward-unicast.

2) Experiment setup: **Evaluation architecture.** The evaluation architecture is illustrated in the Figure 2. In the experiment, a P2P system with one level-2 MDMS overlay connects to various numbers of MDMS overlays at level-3 has been deployed on the large scale French Grid5000 platform [G5k].

Evaluation scenario.

Assume that a data concentrator receive the metering data from 100 smart meters while each MDMS receive the data from 100 data concentrators on average. Thus a MDMS manages $100 \cdot 100 = 10000$ smart meters on average.

We evaluate the communication architecture for large scale AMI with the number of smart meter from 5 millions to 20 millions. In this scenario, the number of MDMS at highest level (level-3) varies from $5000000/10000 = 500$ to $20000000/10000 = 2000$.

Assume that each MDMS level-2 manages 50 MDMSs level-3, thus the number of MDMS at level-2 varies from $500/50 = 10$ to $2000/50 = 40$. This means that the number of children overlay varies from 10 to 40.

The experiments are performed in both no churn and high churn environments to show the efficiency of communication architecture in ideal condition and the resilience of the communication architecture under the failure of MDMS respectively. In churn condition, lifetime mean of parent peers is set to 2 hours while lifetime mean of children peers is set to 1 hours.

Each experiment is run 5 times. The average values and standard deviation of evaluated metrics are plotted in the figures in following sections.

The values of experiment parameters are described in the Table I.

No. of parent overlay	1
No. of children overlay	10, 20, 30, 40
No. of node per child overlay	50
No. of parent nodes	10, 20, 30, 40
Churn	high churn, no churn

TABLE I: Values of experiment parameters

3) Experiment results: Communication efficiency: This section evaluated the ratio of successful communication in combination scheme and upward communications.

Combination-multicast.

The ratio of successful communication performed in combination-multicast scheme is illustrated in the Figure 3.

The lines ”churn” and ”nochurn” represent ratio of successful communication, performed in the systems under churn condition and no churn condition respectively, when the number of children overlays increases from 10 to 40.

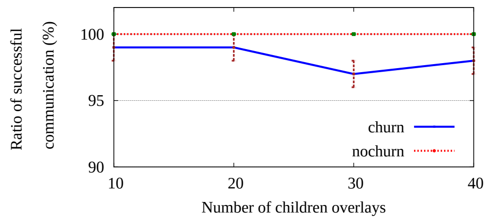

Figure 3: Success ratio in downward-multicast.

The Figure 3 shows that the combination-multicast communication performed in the no churn environment succeed with the ratio of 100%. In the churn environment, the value of this ratio slightly changes in the range from 99% to 97% as the number of children overlay increases from 10 to 40 and the standard deviations are less than 1.5 for all cases.

Combination-unicast and upward-unicast. The Figure 4 illustrates the ratio of successful communication in combination-unicast and upward-unicast schemes. The two lines "combination-unicast" and "upward-unicast" represent the ratio of successful combination-unicast communication and upward-unicast communication respectively, performed in the systems which are under high churn condition, as the number of children overlay rises from 10 to 40.

From the Figure 4 we can see that the line "combination-unicast" is slightly changes in the range from 97% to 99% with the increase of number of children overlays from 10 to 40. The standard deviations are less than 1.5 for all cases. On the other hand, the line "upward-unicast" is horizontal line at value of 1. We did not show the ratio of successful communication in combination-unicast and upward-unicast in no churn condition which are 1 for all cases for the sake of clarity.

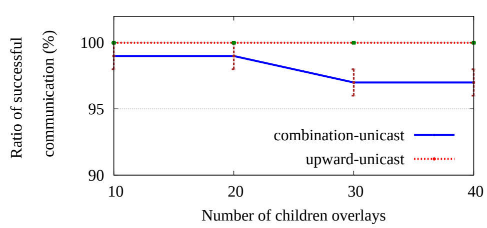

Figure 4: Ratio of successful communication in unicast schemes.

Discussion and Analysis. The high values of ratio of successful communication in both high churn and no churn conditions along with the low standard deviation values show the efficiency and the stable of all evaluated communication schemes: combination-multicast, combination-unicast and upward-unicast. In high churn environment, the slightly changes in values of ratio of successful communication in these communication schemes as the number of children overlay increase from 10 to 40, i.e. from 5 million to 20 million smart meters, shows the scalability of the communication architecture.

4) Experiment results: Maintenance traffic.: The Figure 5 shows the ratio of the traffic generated by a parent peer and a child peer over the traffic generated a Chord peer in the same size network in the churn condition.

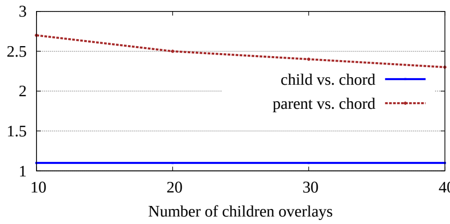

Figure 5: Average traffic generated by parents and children peers.

The two lines "parent vs. chord" and "child vs. chord" show the ratio of the traffic generated by a parent peer and a child peer respectively over the traffic generated a Chord peer in the same size network.

From the Figure 5, we can see that the line "child vs. chord" is horizontal lines at the value of 1.1. The line "parent vs. chord" is slightly decreases from 2.8 to 2.3 as the number of children overlay increase from 10 to 40. The standard deviations are approximately 0 in all cases.

Discussion and Analysis. The fact that the traffic generated by a child peer based on Chord equals 1.1 times the traffic generated by a Chord peer in the same size network, shows that additional traffic generated in a child peer is very small.

We note that the maintenance traffic of a peer, running DHT protocol, increases when the number of peers in the DHT overlay increases. In our experiment, when the number of children overlay increases from 10 to 40, i.e. the number of parent peer also increases, the line "parent vs. chord" is slightly decrease. This means that the maintenance traffic of parent overlay increases with slower rate than the maintenance traffic of Chord overlay as the size of the overlay increases. This proves the scalability of parent overlay in term of maintenance traffic.

V. Conclusions

In this paper, we have introduced a new AMI communication architecture for scalable data collection and management. The architecture is mixing of P2P and client-server in which the MDMSs are geographically distributed and hierarchically organized in a P2P manner. The MDMSs at highest level play the roles of server managing data concentrators.

The analysis shows that the AMI based on our communication architecture is scalable for data collection and management and resilient with failure. Utility can also plan the geographical distribution of MDMSs to have expected latency of collecting data. Smart Grid applications can be deployed in OCs at different levels depend on their characteristics and requirements on latency.

The experiments shows the efficiency of communication schemes in the proposed architecture in term of ratio of successful communication in both high churn and no churn environments. The communication is performed with at least

97% of success under the high churn and with 100% of success in no churn condition. The experiments also show the scalability of our communication architecture in term of maintenance traffic.

REFERENCES

[ami 2008] US Dept. of Energy, Office of Electricity Delivery and Energy Reliability. *Advanced Metering Infrastructure.* 2008

[Rusit et al 2009] S. Rusitschka and C. Gerdes and K. Eger. *A low-cost alternative to smart metering infrastructure based on peer-to-peer technologies.* 6th International Conference on the European Energy Market, 2009. EEM 2009. 2009.

[Jiazh et al 2012] Z. Jiazhen and R.Q. Hu and Y. Qian. *Scalable Distributed Communication Architectures to Support Advanced Metering Infrastructure in Smart Grid.* IEEE Transactions on Parallel and Distributed Systems. 2012.

[Gerdes et al 2009] C. Gerdes and U. Bartlang, and J. Muller. *Vertical Information Integration for Cross Enterprise Business Processes in the Energy Domain.* Proceedings of Agent-Based Technologies and Applications for Enterprise Interoperability. 2009.

[Meili et al 2013] S. Meiling and T. Steinbach and T. C. Schmidt and M. Wählisch. *A Scalable Communication Infrastructure for Smart Grid Applications using Multicast over Public Networks.* Proc. of ACM SAC. 2013.

[Arena et al 2010] M. Arenas-Martinez and S. Herrero-Lopez and A. Sanchez and J.R. Williams and P. Roth and P. Hofmann and A. Zeier. *A Comparative Study of Data Storage and Processing Architectures for the Smart Grid.* Proc. of SmartGridComm. 2010.

[Stand 2010] *SmartGrid/AEIC AMI interoperability standard guidelines for ANSI C12.19 / IEEE 1377 / MC12.19 end device communications and supporting enterprise devices, networks and related accessories.* The Association of Edison Illuminating Companies, Meter and Service Technical Committee report version 2. 2010.

[Queen 2011] E. Queen. *A discussion of smart meters and RF Exposure Issues.* Edison Electric Institute (EEI). 2011.

[Bernaudo et al 2010] D. Bernaudo et al. *SmartGrid/AEIC AMI interoperability standard guidelines for ANSI C12.19 / IEEE 1377 / MC12.19 end device communications and supporting enterprise devices, networks and related accessories.* Online at http://www.aeic.org/meterservice/AEICSmartGridStandardv2-11-19-10.pdf. The Association of Edison Illuminating Companies, Meter and Service Technical Committee report version 2. 2010.

[Tram 2011] H. Tram *Technical and operation considerations in using Smart Metering for outage management.* Transmission and Distribution Conference and Exposition. IEEE/PES. 2008.

[Cascio] J. Cascio *Resilience*. Online at http://www.fastcompany.com/blog/jamais-cascio/open-future/resilience. Accessed September 2013.

[Scala] Wikipedia. *Scalability*. Online at http://en.wikipedia.org/wiki/Scalability. Accessed June 2013.

[AMI] Wikipedia. *Advanced Metering Infrastructure*. Online at http://en.wikipedia.org/wiki/Smart_meter. Accessed June 2013.

[CDN] Wikipedia. *Content Delivery Network*. Online at http://en.wikipedia.org/wiki/Content_delivery_network. Accessed June 2013.

[Cisco 2009] *Cisco definition of Smart Grid.*. Online at http://www.cisco.com/web/strategy/docs/energy/CISCO_IP_INTEROP_STDS_PPR_TO_NIST_WP.pdf. Accessed July 2013.

[Hart 2008] D. G.Hart. *Using AMI to Realize the Smart Grid.* IEEE, 2008.

[Rusitschka et al 2010] S. Rusitschka and K. Eger and C. Gerdes. *Smart Grid Data Cloud: A Model for Utilizing Cloud Computing in the Smart Grid Domain.* Proceedings of IEEE First Int'l Conf. Smart Grid Comm, 2010.

[Khan et al 2013] R. H. Khan and J. Y. Khan. *A comprehensive review of the application characteristics and traffic requirements of a smart grid communications network.* Computer Networks, 2013.

[G5k] *Grid5000 platform*. Online at https://www.grid5000.fr/mediawiki/index.php/Grid5000:Home. Accessed June 2013.

[Stoic et al 2001] I. Stoica and R. Morris and D. Karger and M.F. Kaashoek and H. Balakrishnan. *Chord: A scalable peer-to-peer lookup service for internet applications.* SIGCOMM, 2001

[Castro et al 2006] M. Castro and P. Druschel and A-M . Kermarrec and A. I.T. Rowstron. *Scribe: a large-scale and decentralized application-level multicast infrastructure.* IEEE J.Sel. A. Commun. 2006

[El-Ans et al 2003] S. El-Ansary and L. Alima and P. Brand and S. Haridi. *Efficient Broadcast in Structured P2P Networks.* IPTPS 2003