Traffic Estimation of the PowerMatcher Application for Demand Supply Matching in Smart Grids

Michael Hoefling*, Florian Heimgaertner*, Michael Menth*, and Herman Bontius†
*University of Tuebingen, Chair of Communication Networks, Tuebingen, Germany
Email: {hoefling,florian.heimgaertner,menth}@uni-tuebingen.de
†Liandon B.V., Duiven, Netherlands, Email: herman.bontius@alliander.com

***Abstract*—The electrical grid is changing from a centralized system with predictable and controllable power generation to a system integrating large numbers of distributed energy resources including weather-dependent renewables. As a consequence, the future retail energy market for electrical energy will have many more participants and see more volatile prices than today, creating the need for new communication and trading infrastructures facilitating.**

In this paper, we briefly review PowerMatcher as a possible approach for such an infrastructure, and analytically evaluate its communication characteristics. PowerMatcher is a multi-agent based smart grid communication framework developed by TNO which enables market integration of distributed energy resources and automatic demand supply matching. While the trading side of the framework is well understood, there is no study that considers the communication side. Our results show that PowerMatcher enables scalable retail energy transactions with millions of participants requiring only moderate resources on the communication's side.

I. Introduction

Electricity generation is currently changing from a centralized system with predictable and controllable outputs to a system integrating distributed energy resources (DERs)* including weather-dependent renewables. Such renewable energy sources are less predictable and hard to control [2], [3]. The downside is that we will face variations in supply, with periods of higher or lower renewable energy offers. The deficit must be compensated by other energy sources to avoid outages. This will affect future markets for electrical energy.

In the future retail energy market (REM), any participant will be able to trade energy in retail energy transactions (RETs), i.e., the future REM will have many more participants than today. Instead of a fixed-price contract model, consumers will have dynamic pricing based on predicted supply and demand [4]. Electricity trading intervals will be in the order of minutes or hours, i.e., significantly shorter than today's accounting intervals [5]. As a consequence, the future REM will see more volatile prices than today. New trading infrastructures are necessary as enabling technology [6], [7], [5], [8] to deal with the increased number of REM participants and changing trading dynamics.

The PowerMatcher (PM) communication framework [8], [9] developed by the *Netherlands Organisation for Applied Scientific Research* (TNO) aims at providing such a communication and trading infrastructure at distribution system operator scale, i.e., in the order of millions of customers. The trading aspects of the PM architecture are well understood and have been evaluated in simulation studies and field tests [1], [10], [11], [12]. The communication side of PM has only been investigated with regard to latency measurements in a simulation study [1] demonstrating the scalability of PM for one million households. Investigations of the communication part beyond latency measurements do not exist. This paper addresses that gap through an analytical performance evaluation of the communication part of PM based on a realistic distribution grid model provided by Alliander N.V. and TNO.

This work is structured as follows. We briefly discuss related work in the area of smart grid traffic estimation and characterization in Section II, and present the PM architecture in Section III. In Section IV, we analyze the performance of PM communication leading to our conclusions in Section V.

*In this work the term DER describes "distributed generation, demand response, and electricity storage connected to the distribution grid" [1].

II. Related Work

Budka et al. discuss smart grid bandwidth requirements in LTE macrocells in [13]. They estimate the worst case bandwidth requirements of different smart grid applications, e.g., supervisory control and data acquisition (SCADA), synchrophasors, closed-circuit television (CCTV), mobile workforce, and advanced metering infrastructure (AMI). They apply these estimates to different LTE deployment scenarios and evaluate them with and without meter concentrators placed at substations. They conclude that the frequency spectrum has a direct impact on the bandwidth requirement, which is caused by the LTE cell size. They further claim that bandwidth requirements for smart grid applications may not exceed 5 MB/s per investigated applications per LTE macrocell.

Karagiannis et al. [14] investigate the suitability of LTE for smart grid communication as well. In contrast to [13], they focus on the established *Manufacturing Message Specification* (MMS) framework of the IEC 61850 smart grid protocol suite [15] as communication protocol. Using an NS-3-based simulation model [16], they examine whether MMS over LTE can satisfy the performance requirements for smart metering and remote control communications, and propose architectural modifications. The performance evaluation shows that LTE can be used for the investigated applications as underlying communication technology, given those modifications are applied.

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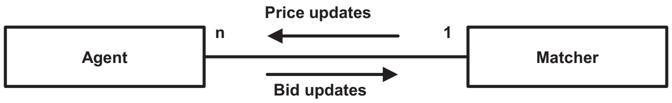

Fig. 1. Generic agent roles in PM: agent and matcher. Agents express bids to a matcher based on the flexibility in supply and demand they represent. The matcher determines the price for its agents based on the supply and demands bids.

Kansal et al. [17] investigate bandwidth and latency requirements for synchrophasor measurements on the transmission grid level. They propose an evaluation framework based on the NS-2 simulator [18], and apply their tool on the Polish power system to evaluate the communication requirements for different zones inside that system. They conclude that the average link bandwidth for the investigated smart grid application should be in the range of $5-10$ Mb/s within one zone, and in the range of $25-75$ Mb/s for inter-zone communication. They further claim that 100 ms latency requirements can be achieved when utilities use a meshed topology for communication.

Deconinck [19] analyzes data volumes and real-time requirements for advanced metering with focus on the two-way property of the communication. He investigates the applicability of powerline communications, smallband and broadband communication over telephone line or cable, 2G and 3G mobile telephone systems, and other radio technologies for advanded metering in the Flanders region of Belgium. He compares those access technologies regarding costs, reachability, bandwidth, latency and reliabilty, and concludes that hybrid communication solutions are needed to satisfy all requirements.

In [20], Luan et al. describe a bottom-up method for smart grid communication network capacity planning. They estimate hourly traffic profiles based on message sizes and intervals for metering, monitoring and telecontrol applications. Based on the traffic profiles and the forecasted number of devices, they derive regional bandwidth requirements for a *blue sky day* scenario featuring normal operation conditions and a *storm day* scenario including large power outages.

III. The PowerMatcher

The PowerMatcher (PM) is a multi-agent based communication framework developed by TNO in the Netherlands [8], [9] which enables RETs on a distribution system operator scale. We give a broad overview on the PM architecture, its general idea, components, and basic interactions. We omit trading related details because they are not within the scope of this work; for further information see [1], [10], [11], [12].

A. General Idea

The PM aims at (1) automatically balancing demand and supply in a cluster of DERs, and (2) market integration of DERs. The PM builds on a hierarchical multi-agent based approach, i.e., within a PM cluster, agents are organized into a logical tree. DERs represent leafs of this tree, and a so-called Auctioneer Agent forms the root of this tree.

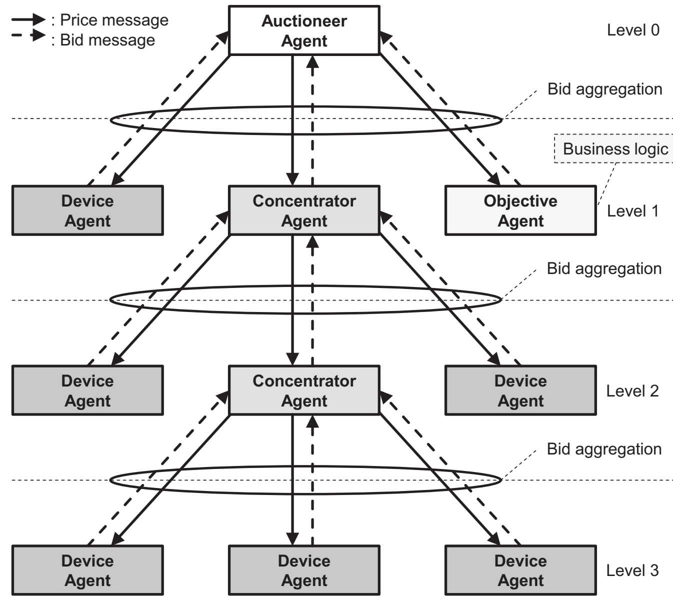

Fig. 2. Overview of the PM architecture and the respective interactions. A hierarchical system of Concentrator Agents disseminates current price information from a central Auctioneer Agent down to Device Agents. It further aggregates the bids of Device Agents towards the Auctioneer Agent. The behavior of the overall system can be influenced by an Objective Agent.

There are two generic *agent roles* in PM as shown in Figure 1: agent and matcher. An *agent* expresses bids to its *matcher* based on the flexibility in supply and demand it represents. The matcher determines the price for its agents based on the supply and demands bids. Any agent is associated with exactly one matcher, and any matcher may be associated with any number of agents.

Besides the generic agent roles, the PM architecture comprises four *agent types*: Device Agents, one Auctioneer Agent, Concentrator Agents, and optionally one Objective Agent. Figure 2 gives an overview of a possible PM architecture and the respective interactions.

B. Components and Interactions

A *Device Agent* (DA) represents a DER device in the PM cluster. It is a control agent which tries to operate the associated physical device in an economically optimal way. An example for such a device may be a photo voltaic panel or controllable consumers, e.g., a fridge and a washing machine. The agent coordinates its actions with all other agents in the cluster by buying or selling energy consumed or produced by the device on an electricity market.

The *Auctioneer Agent* (AA) is the central entity that performs the price-forming process. It concentrates the bids of all Device Agents, Concentrator Agents, and the Objective Agent directly connected to it in a single bid, searches for the equilibrium price and communicates a price update back whenever there is a significant price change.

A *Concentrator Agent* (CA) represents a sub-cluster of DAs or CAs. It concentrates the bids of all subordinate agents in a single bid and communicates this *aggregated bid* to the

AA or to its superordinate CA if it is an intermediate CA. In the opposite direction, it disseminates price updates to the agents in its sub-cluster. A CA may perform bid and price transformation, i.e., intermediate agents can be configured with constraints causing localized price changes. An example would be cutting off the maximum power running over a certain node in the distribution grid by increasing the price. PM calls this feature *congestion management*.

The *Objective Agent* (OA) is an optional agent which allows to change the goal of the cluster. The default goal of the cluster is to balance the demand and supply automatically. If an OA is present, the goal of a cluster might be different, e.g., operation of the cluster as a virtual power plant. This agent interfaces with the business logic of the specific application for the cluster.

Signaling of all interactions is based on two message primitives: bid and price. A *price message* contains the minimum price, maximum price and the number of possible price points n_{steps}. The original price update message which is disseminated from the AA to next-lower agents is also called *market base message*. A bid message contains a so-called *bidcurve* which is a vector of bids sampled according to the predefined settings received by the price message, i.e., the bidcurve comprises n_{steps} price points with each price point having a value between the minimum and the maximum price. At each CA, these bidcurves are aggregated to one bidcurve, and the AA uses these curves to perform its price-forming process.

C. Mapping to Publish/Subscribe Communication

The current implementation of PM runs over the MQTT message bus middleware [21], a broker-based light-weight publish/subscribe (pub/sub) architecture which runs on top of TCP/IP. Mapping PM communication to pub/sub communication is straightforward, and we use Figure 2 as an example.

Figure 2 shows three levels of bid and price aggregation. The AA is located on the top level and acts as publisher for the price topic and as subscriber for the bid topic. Each level of aggregation shall only contain bids and prices of the respective level. To realize this using pub/sub communication, each CA needs to have its own independent set of bid and price topics for its subordinate CAs and DAs. We apply this to the given example in Figure 2, and summarize the necessary topics and their corresponding publishers and subscribers in Table II. To keep the table easy to comprehend, we use the abbreviations for PM participants given in Table I.

The process of mapping PM communication to pub/sub communication can be formalized. We denote n_{bid} as the number of bid topics, n_{price} as the number of price topics, and n_{topics} as the overall number of required topics. We further denote n_{AA} as the number of AAs, and n_{CA} as the number of CAs. One can derive n_{topics}, n_{bid}, and n_{price} based on n_{AA} and n_{CA} using the following formula.

$$n_{topics} = (n_{bid} + n_{price}) = 2 \cdot (n_{AA} + n_{CA}) = 6 \quad (1)$$

TABLE I
ABBREVIATIONS FOR THE PM PARTICIPANTS IN FIGURE 2.

Short Form	Long Form
AA	Auctioneer Agent
OA	Objective Agent
CA-x-y	Concentrator Agent $x-y$; x gives the level of the agent, e.g., 1, 2, or 3; y gives the horizontal position of the agent, e.g., left (L), middle (M), or right (R)
DA-x-y	Device Agent $x-y$; x gives the level of the agent, e.g., 1, 2, or 3; y gives the horizontal position of the agent, e.g., left (L), middle (M), or right (R)

TABLE II
OVERVIEW ON TOPICS NECESSARY TO MAP PM COMMUNICATION TO PUB/SUB COMMUNICATION.

Topic	Publisher	Subscriber
Auct_Bid	DA-1-L, CA-1-M, OA	AA
Auct_Price	AA	DA-1-L, CA-1-M, OA
CA-1_Bid	DA-2-L, CA-2-M, DA-2-R	CA-1-M
CA-1_Price	CA-1-M	DA-2-L, CA-2-M, DA-2-R
CA-2_Bid	DA-3-L, DA-3-M, DA-3-R	CA-2-M
CA-2_Price	CA-2-M	DA-3-L, DA-3-M, DA-3-R

Applied to our example given in Figure 2, we have $n_{AA} = 1$ and $n_{CA} = 2$. Thus, we calculate $n_{topics} = 6$ distinct topics. This is in line with the previously conducted manual mapping of PM communication to pub/sub communication.

IV. PERFORMANCE EVALUATION

We now investigate the performance of PM communication. We base our studies on a distribution grid model provided by the Dutch utility Alliander N.V. and TNO. We first give a brief description of the model, define our metrics, and analyze the model.

A. Model Description

Table III summarizes the important key parameters for the performance evaluation of the investigated scenario. The model comprises of 2 million households or prosumers. Each household is represented by a CA, and has internally between 1 and 20 DAs. Two million households are typically subdivided into 20 to 50 trusted clusters, each containing an AA. That means, there are at most $n_{households}^{cluster} = \frac{2000000}{20} = 100000$ households per trusted cluster. Within each cluster, there are 100 to 1000 concentrators active, each concentrating 1000 down to 100 households. Computing power and network bandwidth are limiting factors for the size of each concentrator's subcluster.

The communication behavior of the model is as follows. The AA sends out a price update at least every 5 minutes. Each price message is 16 B large. Each bid and aggregated bid message is 2 kB large. Each CA and DA reacts immediately on the price update and may reply with a bid message also at least every 5 minutes. MQTT is used as communication middleware between the DAs at the households and the AA of each cluster.

TABLE III
KEY PARAMETERS FOR THE PERFORMANCE EVALUATION OF THE INVESTIGATED PM SCENARIO.

Variable	Value	Description
$n_{households}$	2000000	Number of households
$n_{clusters}$	20	Number of clusters
$n^{cluster}_{households}$	100000	Households per cluster
$n^{cluster}_{AA}$	1	Number of AAs per cluster
$n^{cluster}_{OA}$	1	Number of OAs per cluster
n^1_{CA}	$100 - 1000$	Number of CAs on level 1
n^2_{CA}	$1000 - 100$	Number of CAs on level 2 per CA on level 1
$n^{cluster}_{CA}$	$n^1_{CA} + n^1_{CA} \cdot n^2_{CA}$	Overall number of CAs per cluster
n_{DA}	$1 - 20$	Number of DAs per CA on level 2
s_{price}	16 B	Size of a price message
s_{bid}	2 kB	Size of a bid message
f^{min}_{price}	$\frac{1}{5} \cdot \frac{1}{\text{min}}$	Minimum price update rate

B. Performance Metrics and Analysis

We derive and calculate performance metrics per cluster first, and scale it to full model size later.

For each cluster, the number of publishers and subscribers that need to be supported can be calculated by counting the number of involved AAs, OAs, CAs and DAs. Each of them acts as publisher and subscriber, i.e., the number of publishers and subscribers is equal because the communication in PM follows a bidirectional pattern. We base our calculations for $n^{min}_{subscriber}$ on the minimum number of DAs per household $n^{min}_{DA} = 1$, and the minimum number of CAs per cluster $min(n^{cluster}_{CA})$ which means $n^1_{CA} = 100$ and $n^2_{CA} = 1000$. The calculations for $n^{max}_{subscriber}$ are based on the respective maximum values $n^{max}_{DA} = 20$, and $n^1_{CA} = 1000$ and $n^2_{CA} = 100$.

$$\begin{aligned} n^{min}_{subscriber} &= n^{min}_{publisher} \\ &= n_{AA} + n^{cluster}_{OA} + min(n^{cluster}_{CA}) + n^{min}_{DA} \\ &= 1 + 1 + (100 + 100 \cdot 1000) + 1000 \cdot 100 \cdot 1 \\ &= 200102 \end{aligned} \tag{2}$$

$$\begin{aligned} n^{max}_{subscriber} &= n^{max}_{publisher} \\ &= n_{AA} + n^{cluster}_{OA} + max(n^{cluster}_{CA}) + n^{max}_{DA} \\ &= 1 + 1 + (1000 + 1000 \cdot 100) + 1000 \cdot 100 \cdot 20 \\ &= 2101002 \end{aligned} \tag{3}$$

This gives a lower and upper bound for the number of publishers and subscribers that need to be supported if each household has between 1 and 20 DAs running. For the remainder of this performance evaluation, we use $max(n^{cluster}_{CA})$ for the number of CAs per cluster. We derive the number of topics which have to be supported based on Equation 1.

$$\begin{aligned} n_{topics} &= (n_{bid} + n_{price}) = 2 \cdot \left(1 + max(n^{cluster}_{CA})\right) \\ &= 2 \cdot (1 + 1000 + 1000 \cdot 100) = 202002 \end{aligned} \tag{4}$$

We estimate the minimum data rate that each agent is expected to handle. The AA receives bids only from its subordinate CAs and the OA, and sends price updates to these nodes. Therefore, the expected minimum load for the AA is derived as follows.

$$\begin{aligned} L^{AA}_{sent} &= s_{price} \cdot f^{min}_{price} = 16\,\text{B} \cdot \frac{1}{5} \cdot \frac{1}{\text{min}} = 0.43\,\text{b/s} \\ L^{AA}_{recv} &= (n^{cluster}_{OA} + n^1_{CA}) \cdot s_{bid} \cdot f^{min}_{price} \\ &= (1 + 1000) \cdot 2\,\text{kB} \cdot \frac{1}{5} \cdot \frac{1}{\text{min}} = 54.67\,\text{kb/s} \\ L_{AA} &= max\left(L^{AA}_{sent}, L^{AA}_{recv}\right) = 54.67\,\text{kb/s} \end{aligned} \tag{5}$$

Intermediate CAs receive price updates from the AA, bids from their subordinate CAs or DAs. In the other direction, intermediate CAs send the aggregated bid to the AA and forward the price update to all subordinate CAs and DAs. For each intermediate CA, the expected minimum load $L^{intermediate}_{CA}$ is derived as follows.

$$\begin{aligned} L^{intermed.,sent}_{CA} &= (s_{price} + s_{bid}) \cdot f^{min}_{price} \\ &= (16\,\text{B} + 2\,\text{kB}) \cdot \frac{1}{5} \cdot \frac{1}{\text{min}} = 55.04\,\text{b/s} \\ L^{intermed.,recv}_{CA} &= \left(n^2_{CA} \cdot s_{bid} + n^{cluster}_{AA} \cdot s_{price}\right) \cdot f^{min}_{price} \\ &= (100 \cdot 2\,\text{kB} + 1 \cdot 16\,\text{B}) \cdot \frac{1}{5} \cdot \frac{1}{\text{min}} \\ &= 5.46\,\text{kb/s} \\ L^{intermediate}_{CA} &= max\left(L^{intermed.,sent}_{CA}, L^{intermed.,recv}_{CA}\right) \\ &= 5.46\,\text{kb/s} \end{aligned} \tag{6}$$

Household CAs receive price updates from their superordinate CA and bids from their subordinate DAs. In the other direction, they send the aggregated bid to the superordinate CA and forward the price update to all subordinate DAs. For each household CA, the expected minimum load is derived as follows.

$$\begin{aligned} L^{household,sent}_{CA} &= (s_{price} + s_{bid}) \cdot f^{min}_{price} \\ &= L^{intermed.,sent}_{CA} = 55.04\,\text{b/s} \\ L^{household,recv}_{CA} &= (n_{DA} \cdot s_{bid} + s_{price}) \cdot f^{min}_{price} \\ &= (20 \cdot 2\,\text{kB} + 16\,\text{B}) \cdot \frac{1}{5} \cdot \frac{1}{\text{min}} \\ &= 1.07\,\text{kb/s} \\ L^{household}_{CA} &= L^{household,sent}_{CA} + L^{household,recv}_{CA} \\ &= 55.04\,\text{b/s} + 1.07\,\text{kb/s} = 1.12\,\text{kb/s} \end{aligned} \tag{7}$$

Finally, DAs receive price updates from their superordinate CA and send bids to it. For each DA, the expected minimum load is derived as follows because bid messages are larger than price messages.

$$L_{DA} = s_{bid} \cdot f^{min}_{price} = 2\,\text{kB} \cdot \frac{1}{5} \cdot \frac{1}{\text{min}} = 54.61\,\text{b/s} \tag{8}$$

As shown above, the expected peak load for the AA is largest. When we scale the numbers to 2 million households, the required network I/O capacity per node and also the necessary network bandwidth remains in a manageable region so that it can be realized with off-the-shelf technology.

Another important metric is the expected data rate per topic because this has a direct impact on the provisioning of the MQTT brokers responsible for these topics. We derive minimum and maximum data rates per topic on the assumptions that bid topics in general are larger because bid messages are 128 times larger than price messages. Further, we consider the minimum and maximum number of agents which corresponds to 1 (DAs) and 1000 (CAs) respectively. Based on that, we calculate the minimum and maximum expected data rate per topic as follows.

$$L_{topic}^{min} = s_{bid} \cdot f_{price}^{min} = 2\,\text{kB} \cdot \frac{1}{5} \cdot \frac{1}{\text{min}} = 54.61\,\text{b/s} \quad (9)$$

$$L_{topic}^{max} = max(n_{CA}^{1}, n_{CA}^{2}) \cdot s_{bid} \cdot f_{price}^{min} = $$
$$= max(1000, 100) \cdot 2\,\text{kB} \cdot \frac{1}{5} \cdot \frac{1}{\text{min}} = 54.61\,\text{kb/s} \quad (10)$$

These rates are lower bounds as the actual message rate may be higher than f_{price}^{min}. We take the maximum expected topic data rate and extrapolate the system-wide overall topic load which has to be managed by the MQTT brokers. This load has to be distributed appropriately among all MQTT brokers of the system.

$$L_{topic}^{all} = n_{topics} \cdot L_{topic}^{max} = 11.03\,\text{Gb/s} \quad (11)$$

We assume that MQTT brokers are able to process data with at least $L_{broker}^{throughput}$†. We can therefore express the minimum number of brokers needed to handle the overall topic data load as a function of $L_{broker}^{throughput}$.

$$n_{broker}^{min}(L_{broker}^{throughput}) = \left\lceil \frac{L_{topic}^{all}}{L_{broker}^{throughput}} \right\rceil \quad (12)$$

Figure 3 shows the minimum number of brokers n_{broker}^{min} for varying broker throughputs $L_{broker}^{throughput}$ ranging from 100 Mb/s to 1000 Mb/s. The line is interpreted as follows: for a maximum broker throughput x on the x-axis, the y-axis gives the minimum number of brokers that are necessary to handle the overall topic load L_{topic}^{all} when the topic load is evenly distributed among all brokers. When brokers are able to process and transfer data with at least 500 Mb/s, a minimum number of 22 brokers is necessary for a cluster with 100.000 households. When brokers are significantly slower, e.g., $L_{broker}^{throughput} = 100\,\text{Mb/s}$, a minimum number of 110 brokers is necessary for the same cluster.

CAs and the AA have to cache the last bids from all their subordinate CAs and DAs until a new bid is received. Because each agent shall send or resend its bid every 5 minutes, we propose a minimum caching time of 10 minutes for each bid.

$$t_{cache}^{min} = 10 \text{ minutes} \quad (13)$$

Based on this, we can estimate the minimum storage needed per agent. We denote the respective capacities as C_x^y with x representing the agent type and y the subclass, if applicable.

†This summarizes processing and network throughput, whichever dominates as limiting factor.

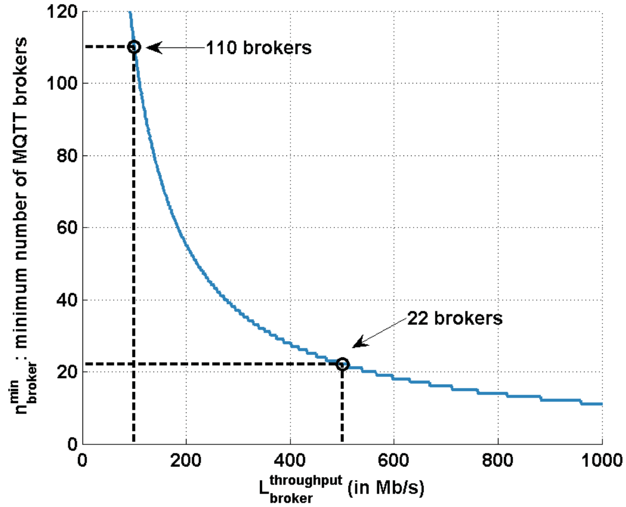

Fig. 3. The minimum number of MQTT brokers n_{broker}^{min} depends on the maximum data throughput of a broker $L_{broker}^{throughput}$. For a cluster with 100.000 households, 22 brokers with a throughput of 500 Mb/s are necessary to handle the overall topic data load. In contrast, 110 brokers would be necessary for $L_{broker}^{throughput} = 100\,\text{Mb/s}$.

We base our calculations on the assumption that $n_{CA}^1 = 1000$, $n_{CA}^2 = 100$, and $n_{DA} = 20$.

$$C_{AA} = (1 + n_{CA}^1) \cdot s_{bid} = 1.96\,\text{MB} \quad (14)$$
$$C_{CA}^{intermediate} = n_{CA}^2 \cdot s_{bid} = 0.20\,\text{MB} \quad (15)$$
$$C_{CA}^{household} = n_{DA} \cdot s_{bid} = 20.00\,\text{kB} \quad (16)$$
$$C_{DA} = s_{bid} = 2.00\,\text{kB} \quad (17)$$

These relatively small numbers for a base of 100.000 households is because each intermediate CA aggregates all bids into one bid, i.e., strong aggregation significantly reduces the amount of data which needs to be cached. When we scale these numbers to 2 million households, the AA still only has to have about 40 MB of storage for the last bids. The numbers scale linearly with the storage time should old bids be stored longer for statistical analysis, e.g., if is set to a very large value.

C. Summary of Results

We summarize the evaluation results in Table IV. The listed values in the second column are valid for clusters of 100000 households, 1 AA, 1000 first-level CAs, 100 second-level CAs per first-level CA, and up to 20 DAs per second-level CA. The listed values in the third column represent the linearly scaled values for 2000000 households, i.e., 20 clusters with 100000 households each.

Our results show that the communication requirements of a large-scale PM deployment can be handled with todays communication technology. RETs with millions of participants possibly require only moderate resources on the communication's side. We identify two main reasons for the observed traffic characteristics. The first reason is price and bid aggregation at each intermediate agent which leads to a significant

TABLE IV
EVALUATION RESULTS FOR 100000 HOUSEHOLDS (SECOND COLUMN) AND 2000000 HOUSEHOLDS (THIRD COLUMN).

Variable	100000 **households**	2000000 **households**
$n_{subscriber}^{min}$	200102	4002040
$n_{subscriber}^{max}$	2101002	42020040
$n_{publisher}^{min}$	200102	4002040
$n_{publisher}^{max}$	2101002	42020040
n_{topics}	202002	4040040
L_{AA}	54.67 kb/s	54.67 kb/s
$L_{CA}^{intermediate}$	5.46 kb/s	5.46 kb/s
$L_{CA}^{household}$	1.12 kb/s	1.12 kb/s
L_{DA}	54.61 b/s	54.61 b/s
L_{topic}^{min}	54.61 b/s	54.61 b/s
L_{topic}^{max}	54.61 kb/s	54.61 kb/s
L_{topic}^{all}	11.03 Gb/s	220.60 Gb/s
$L_{broker}^{throughput}$	500.00 Mb/s	500.00 Mb/s
n_{broker}^{min}	22	440
t_{cache}^{min}	10 mins	10 mins
t_{cache}^{max}	Unlimited	Unlimited
C_{AA}	1.96 MB	1.96 MB
$C_{CA}^{intermediate}$	0.20 MB	0.20 MB
$C_{CA}^{household}$	20.00 kB	20.00 kB
C_{DA}	2.00 kB	2.00 kB

reduction in traffic volume. The second reason is the use of pub/sub as information dissemination paradigm on the communication layer, i.e., each agent only has to publish one message to the pub/sub framework instead of sending separate messages to subordinate agents. The latter simplifies the agents internal communication logic.

V. CONCLUSIONS

The electrical grid is currently changing from a centralized system with predictable and controllable outputs to a system integrating DERs including weather-dependent renewables. In the future REM, any participant will be able to trade energy based on predicted supply and demand. As a consequence, the future REM will have many more participants and see more volatile prices than today. New trading infrastructures are necessary as enabling technology. The PM communication framework by TNO aims at providing such a communication and trading infrastructure at distribution system operator scale.

In this paper, we analytically evaluated the communication performance of the PM architecture for a large-scale deployment model provided by Alliander N.V. and TNO. Our results show that PM enables scalable RETs with millions of participants requiring only moderate resources on the communication's side. The main reasons for scalable and efficient communication in PM are price and bid aggregation on the application layer, and the use of pub/sub as information dissemination paradigm on the communication layer.

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