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Energy Resource Management in Smart Grid

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***Abstract*—Smart grids are characterized by a dynamic nature in which distributed energy resources (DER's) changes internal states and availability over time. Distributed Energy Resources (DER's) and the distributed control system will thus be required to automatically configure itself to this dynamic behavior. This paper[1] addresses communication and control challenges to achieve a plug'n'play type of DER management. A use case with Electric Vehicles is considered because of its high dynamic behavior in smart grid. In particular, the problem of making correct decisions on which controller out of many, an EV shall be operated by will be addressed. This is not an isolated control problem, but for reliable decisions also requires to take into account characteristics of the involved networks in combination with the dynamics of the decision information at the controllers. In the paper we propose a decentralized (de)register/reconfiguration protocol and evaluate its ability to lead to reliable decisions of EV assignments to controllers in a hierarchical multi control system.**

***Index Terms*—Smart Grid, AMI, DER, DER Management, Control, Communication.**

I. Introduction and Background

The next generation of electric power infrastructure is called the Smart Grid. The new grid system makes it possible to utilize existing distributed energy resources (DER) and thereby optimize the demand and response (DR) using Direct Load Control (DLC) [1]. The DER can be e.g. electric vehicles or heat pumps, which can take load off or shift load in time on the grid, and thereby contribute to load balancing on the grid and save the utility companies to pay for neighbor countries to take off the load [2][3]. Consumers having different DERs available are also called prosumer, which are costumers who are able to consume and produce power and are connected through an Advanced Metering Infrastructure (AMI) [4]. Being able to let the utility company use the DERs from their costumers, entitles the costumers to get benefits on their electricity bills.

In order for the utility companies to make better load balancing on the grid using the DERs of their costumers, control algorithms have to be developed, which are able to handle these dynamic resources. To link the resources to the utility company a proper communication network infrastructure have to be established, that can handle the requirements from the control algorithms and the dynamics of the DERs. Figure 1 shows a high level view of the scenario envisioned. In urban areas natural places for charging of EV's exists, e.g. in the domain of public transportation, taxis, parking areas. Households may also offer charging capacity to the grid. Common to all these, is that its current energy potentials and demands needs to be communicated to power grid controller in order to facilitate power grid control.

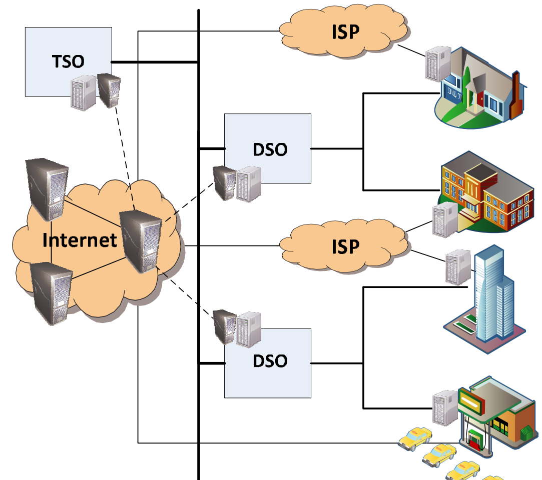

Fig. 1. The figure illustrate a high level view, where the TSO and DSO customers are connected to the grid and how they are communication is connected through the internet connection.

The system consists of a large numbers of prosumers whose energy balance is being monitored over existing communication infrastructure, e.g. ISP's, cellular, fiber, and evaluated in a system of controllers that via the TSO and DSO's ensures the energy balance. Estimation and prediction of grid state is done as a part of the control system, which is divided into a subcontrol structure (described later in Section II), containing several servers that executes the control algorithms.

Each time new entities are introduced to the smart grid system, these new entities needs to be included not only in a communication framework but also in a distributed control loop. The inclusion of new nodes should happen in a plug'n'play manor, since manual setup procedures is not only cumbersome for the end user, but does not necessarily gives the best configuration as several metrics and constraints needs to be considered.

Selecting the wrong control server is costly for the system, as a reconfiguration procedure later on will need to be carried out, taking the entity out of the control loop for some period. Hence minimization of the risk for selecting the wrong control server in the first place is highly desirable. This is exactly

[1]This is an invited paper for the session on "Intelligent Monitoring, Control, and Security of Critical Infrastructure Systems"

the topic of the paper. The involved subsystems and their properties complicates matter of which control loop an energy resource should become a part of when entering a running system, and some of these information (examples shown in the below bullet list) are also dynamic which poses a challenge to the reliability of the control server selection.

- Network properties (delay, jitter, packet loss, data rates, congestion levels)
- Control properties (information types, control methods, control frequency)
- Energy grid properties (line capacity, existing energy flows)

The dynamic (re)entry of controllable energy resources are most prominent in charging of electric vehicles, however, is also relevant for households or building upon installation of smart grid support mechanisms (although, with a much lower dynamics than the EV type of scenario). Hence, we will in this paper focus on the EV scenario type due to the challenging dynamics.

The contribution of this paper is a high level protocol description of automatic discovery of the correct control subsystem, as well its ability to select the correct control server by proper adjustment of a single protocol parameter. We do not consider the actual selection algorithm in this paper.

II. Control system concept

A. Control system architecture

A control system ensures the energy balance of the grid via any available controllable elements in the power grid (e.g. household equipments, electric vehicles, heat pumps). The concept is shown in Figure 2 where a hierarchical control system affects the configuration of the grid, based on the inputs coming from measurements of power consumptions as well as predictions of consumption and production. The control concept is a Model Predictive Controller and is described in further details in [5]. This concept allows for plug and play control concept, i.e. the control structure is designed to allow elements joining and leaving the structure as needed, which for electric vehicles is most interesting.

A core element in the system is the so-called aggregator, which ensures control of a set of DER's that shares similar control profiles. A shared profile enables the control algorithms at the aggregator to optimize its operation for the particular type of DER, [5]. The aggregator is responsible for within its operational range, to send command signals to the DER on how they should operate on the grid. For electric vehicles that would be charging signals, indicating when and by how much the vehicle should charge.

The high level controller ensures the overall operation of all of the aggregators and ensures that these are working together efficiently. Via smart meters, deployed sensors and other sensing type of devices, measurements of the system state is provided over the different access networks to the control system. In practice it may not be the high level controller that receives the information feed back into the control system as

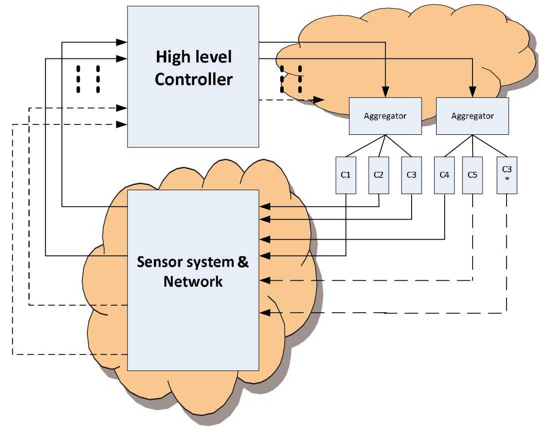

Fig. 2. Control concept of a hierarchical control system. The high level controller effects the aggregators how they are supposed to manage their customers (energy resources) and thereby affect the configuration of the grid, based on the inputs from measurements of power consumptions as well as predictions of consumption and production

shown, but the concept is that these information is creating a control loop.

That the control algorithm will need to be executed within fixed time intervals, makes time a critical parameter for the control system, and hereby puts certain constraints on the scalability of the system. As the information being feed back into the system cannot be transmitted efficiently all at the same time to one server, and charge signals may also not efficiently be transmitted to the DER's at the same time from one server without messages has to wait in queues, several aggregators of same kind will be needed for load balancing of network traffic.

B. Power profile

The key feature of the control algorithm is that the aggregators are controlling their individual customer in the control hierarchy based on a flexibility power profile. A flexibility power profile is some description of how flexible the control customer is with respect to energy intake. An example, an electric vehicle, could has some constraints on when it should start charging, when it should be finished, maximum and minimum power and max charges. An example is shown in Figure 3.

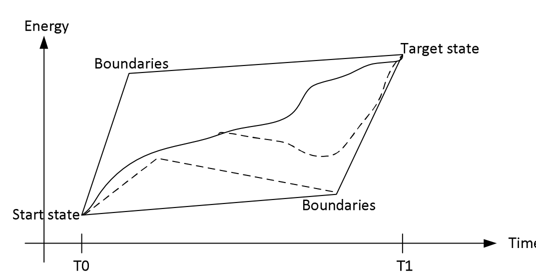

Fig. 3. Example power profile of an electric vehicle.

The starting point at time T_0 and ending time T_1 dictates the overall time frame of the charging process, whereas the flanks indicates the max and min allowable charging power. The information assumed is here to be provided by the car battery manufacturer and available to the system. There may be further recommended charging profiles, in Figure 3 illustrated by the dotted, straight lines at the low boundaries. Finally, the objective is then to have the car battery charged such that the energy state of the battery is kept within these boundaries. Potentially, during charging, a drain of energy may be requested from the aggregators (here exemplified by the alternative dotted energy level curve). In the latter case, the charging still needs to meet the power charging constraint and still meet the full charged battery at time T_1.

C. Metrics for aggregator assignment

In order to properly assign a resource to an aggregator, some key information must be known for the entity that makes the assignment:

- **Power profile**: Each aggregator performs best when controlling resources with same (or nearly) the same power profile. Thus, a new resource shall need to be attached to aggregators that already controls similar types of resources. Data structure describing the power profile is required information.
- **Physical grid**: A resource is provided power from the power grid, which implies some localisation constraints, e.g. an EV in Denmark should not be connected to an aggregator responsible in Italy. Geographical position is required information.
- **Communication**: The connectivity between the resource and the aggregator is for control timing constraints highly delay sensitive. Thus, packet delay and variation in delay (PDV) is a crusial parameters along with bandwidth. If the bandwidth is not big enough delay and packet loss will appear in the network.
- **Node limitations of aggregators**: Each aggregator has a node capacity which shall not be exceeded. Number of nodes already assigned are required information.

Based upon these information, a decision shall be made to find the most suitable aggregator to be assigned to. These information are, however, dynamic and changes over time, hence challenging the decision. Any wrong decisions may lead to unnecessary reconfiguration later on and shall be considered costly.

III. Aggregator assignment protocol

In the work we will present in this paper, we will focus on the proposed registration/deregistration and reconfiguration protocol.

A. (De)Registration procedure

The role of the network in smart grids is not only to ensure connectivity between the different involved logic entities; controllers, measurement points, DER's, but also the support of discovery and negotiation of arriving/departing DER's. Upon arrival of a new resource, a decision must be made to which aggregator it shall be assigned to. The proposed high level decision process is illustrated in Figure 4. In the background the High Level Controller (HLC) interacts with the associated aggregators on a periodic basis as a part of its normal operation. Updates are send to the HLC from the aggregators about their current status, and in return they are given instructions on how to operate. Based on these instructions from the HLC, and aggregator can issue control commands to the resource as it too have received updates from its associated energy resource. The process is shown in Figure 4 in which Customer 1 interacts with aggregator 1.

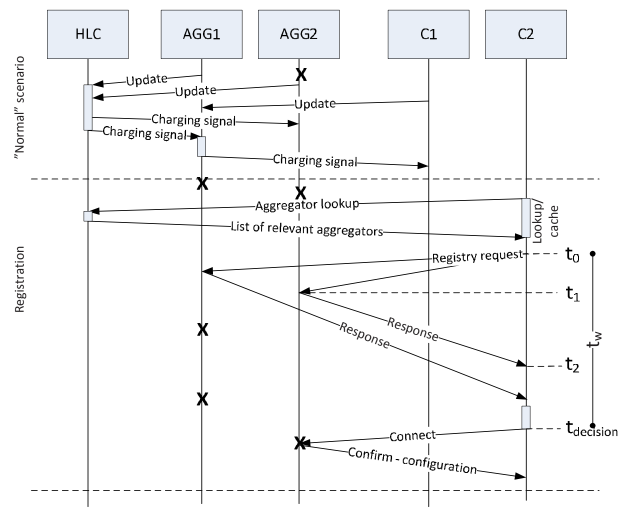

Fig. 4. Registration procedure: The client sends requests and waits T_w until making a decision which aggregator to associate to. An event happens for aggregator 1 while its response was returning, hence the decision is not reliable.

At some point in time, a new resource, $C2$, becomes available to the system. At first, this contacts a directory to lookup potential aggregator candidates. Since the HLC already is aware of the aggregators this is a natural candidate for such lookup service, or it could be a name based lookup, e.g. DNS. The HLC responds to the lookup message with the addresses of relevant aggregators $C2$ may be connecting to. This information may be cached for later faster lookups. The resource then sends a assignment requests to all of the possible potential aggregators that includes a detailed flexibility profile. A subset of the potential aggregators decides upon a rough profile match to reply to the request with the response that it is a potential candidate for association. The resource gathers the response from a number of potential aggregators within a given waiting time ($T_{Waiting}$) and determines the aggregator which fits the best to the resources demands. The resource then sends a connect message to that aggregator, and will hereafter be included into the control loop of that aggregator. Normal operation will then continue until the resource decides to leave again, by which it simply sends a deregistry message to its aggregator. The change of flexibility upon this deregistration is automatically updated by the aggregator and mitigated to the HLC, which by the nature of the control strategy is effectively handled.

Since the information from the aggregators is used by the client to make a decision, it is important that this information matches at both the resource and the aggregator side. If, for example, a registry or deregistry has happened meanwhile $C2$ is waiting for responses (e.g. due to registry or deregistry of other resources), the decision of $C2$ may not be reliable. This happens for aggregator 1 in Figure 4, where events are marked with a 'X' along the time axis.

B. Reconfiguration procedure

The situation of the resource, the grid, the communication network is not static, and events will occur that either changes the profile, the state of the grid or the communication network in such way that the resource should need to change aggregator. For exampel, if the latency between the current aggregator and the resource becomes high, the network may need to change which may lead to other and better choices of aggregators. In this case, the event may trigger a registry procedure, but without the lookup since the resource already has knowledge of potential aggregators. The procedure is shown in Figure 5.

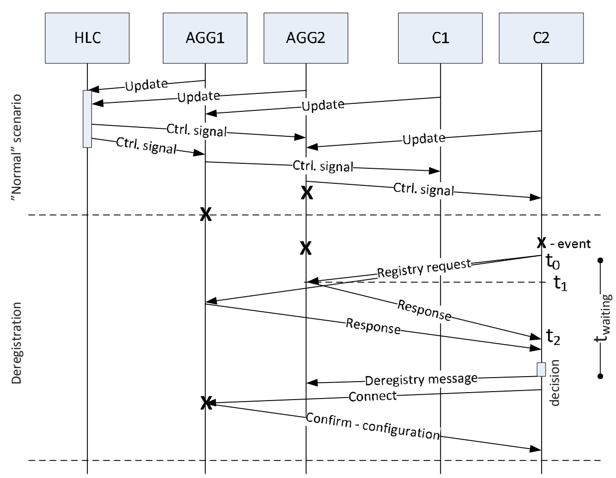

Fig. 5. Deregistration procedure: An event triggers a change of aggregator association, leading to a new registration procedure. No events happens at the aggregators before a decision is made, hence the decision is reliable.

Here, the problem is similar to the registry situation, however upon the change the DER will be in an unknown state as it does not deliver any updates to the system. Alternatively, an overlap could be introduced such the deregistration message is only triggered once the registration of another aggregator has been successful. But that leads to potential double registration issues that are also undesirable. Further, the reconfiguration costs in terms of traffic overhead is undesirable, so this scenario is in fact, a last resort to solve a problem and should be avoided. But the principle of waiting the time period $T_{waiting}$ before deciding on which aggregator to assign to, is the same as for the assignment procedure.

IV. System model of assignment process

A. Reliability model of assignment procedure with waiting time

In the model we present in the following, we assume responses that have not been received before the waiting time has ended, will lead to an unreliable decision as the decision taken then will be based upon incomplete information. We specify the waiting time, t_w as the time between the initial requests are send to the N aggregators at time t_0 (see Figure 4 or 5), until the decision of which aggregator the resource shall be assigned to at time $t_{decision}$, and the delays $d_1 = t_1 - t_0$ and $d_2 = t_2 - t_1$. Then, we consider the probability of making an unreliable decision as the probability that no event occurred during the waiting time period. We call this the mismatch probability, (mmPr). This can be expressed as shown in Equation (1).

$$mmPr_i^{tw} = \mathbf{Pr}(no \quad events \quad in \quad [t1; tw]) \tag{1}$$

$$\begin{aligned} &= 1 - \int_0^{T_w} v[t1; t_w] Pr(d_2 < t_w - t1 | d_1 = t) f_{d1}(t) dt \\ &= 1 - \int_0^{T_w} \left(1 - \int_0^{T_w - t} f_{e,i}(\tau) d\tau\right) \\ &\quad \cdot \int_0^{T_w - t} f_{d_2}(s) ds f_{d_{1,i}}(t) dt. \end{aligned} \tag{2}$$

with $f_{e,i}$ being the distribution of the event interarrival times for the ith aggregator, $f_{d_x,i}$ the delay distributions to the ith aggregator. Under exponential event and symmetric and i.i.d. delay distributions assumptions Equation (2) can be expressed as

$$\begin{aligned} mmPr_i^{tw} &= 1 - \nu \Bigg(exp(-\lambda T_w) \frac{1 - exp(-T_w(\nu - \lambda))}{\nu - \lambda} \\ &\quad - exp(-T_w(\lambda + T_w)) \frac{1 - exp(-\lambda T_w)}{\lambda} \Bigg) \end{aligned} \tag{3}$$

As it can be seen, when the delay rate is equal to the event rate, the first part of the equation breaks down. However, this case is easily solved by the use of l'Hospitals rule of convergence. Thus for the special case of equal delay and event rates, the mmPr can be calculated as

$$\begin{aligned} mmPr_i^{tw} &= 1 - \nu_i \Bigg(exp(-\lambda_i T_w) T_w \\ &\quad - exp(-T_w(\lambda + T_w)) \frac{1 - exp(-\lambda T_w)}{\lambda} \Bigg) \end{aligned} \tag{4}$$

B. Evaluation of reliability with single aggregators

Using the explained $mmPr$ model, Figure 6 shows the resulting mismatch probability for varying mean event inter arrival times for one aggregator, e.g. the mean time intervals between (de)registrations of electric vehicle in one aggregator as well as for different chosen values of waiting times.

Figure 6 shows that not only does the event time affect the mmPr, as it was expected [6], but the selection of waiting time has a significant impact on the mmPr. That is, if we select it too short, then the mmPr becomes higher. The lower bound illustrates when there is no waiting time and the information is used at the moment when it has been received, [6]. However

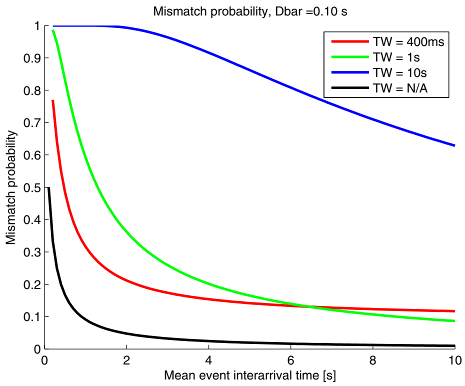

Fig. 6. mmPr with varying event inter arrival times and for different waiting times. The low boundary is when information is used immediately after receiving the response.

it is only usable for the case of one aggregator which means there is no other aggregator to choose from anyway.

C. Evaluation of reliability with multiple aggregators

Looking at the communication scenario in Figure 5, multiple aggregators will need to respond to the request coming from an EV, and only one waiting time is involved, ie. t_w explained in Section IV. The response from an aggregator will be arriving earlier than others. To see how this can impact the mmPr, Table I is used, which shows aggregators with different characteristics. Using these values from Table I, the influence on the mmPr is illustrated in Figure 7.

TABLE I
PARAMETERS FOR AGGREGATORS USED IN EVALUATION

Aggregator	Avg. delay	Avg. event time
Aggr. 1	70 ms	78 sec
Aggr. 2	50 ms	18 sec
Aggr. 3	531 ms	20 sec
Aggr. 4	829 ms	92 sec
Aggr. 5	732 ms	25 sec

The result shown in Figure 7 illustrates it is not trivial to decide a waiting time, since the best choice for one aggregator, is not necessarily the best for the other aggregators. If a waiting time is chosen too far to the right, to fit an aggregator, information from the other ones will lead to larger caching time until the decision point, leading to a higher mmPr. In effect, Figure 7 shows the balance between selecting the waiting time too short and too long.

D. Finding an optimal waiting time

Basically, what we need to do is to find a reasonable balance between waiting too short and waiting too long to avoid either miss responsens or use outdated information. We define the average mmPr as

$$mmPr_{avg} = \frac{1}{N}\sum_{i=1}^{N} mmPr_i^{tw}(D, E, T_w)$$

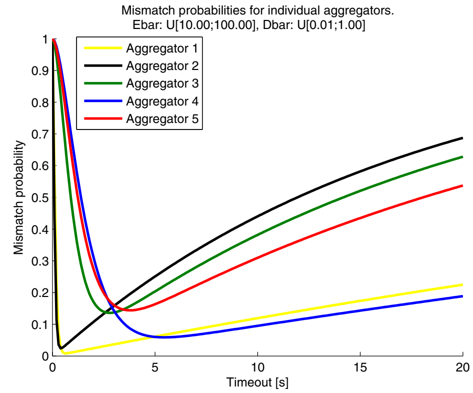

Fig. 7. mmPr with varying waiting times for 5 different aggregators using random delays and event process parameters.

A plot of the average mmPr for the 5 aggregators from Table I is shown in Figure 8.

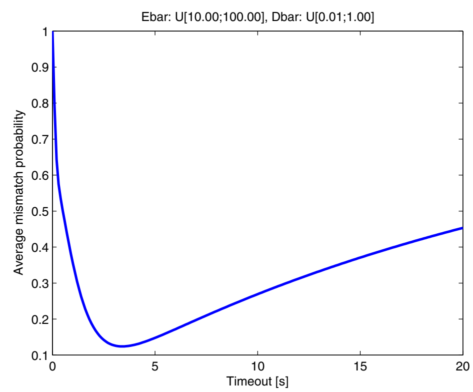

Fig. 8. Average mmPr with varying waiting times for 5 different aggregators using random delays and event process parameters.

A numerical search algorithm for locating the waiting time that leads to a minimum mmPr is then applied and for this case, the optimal waiting time is found to be T_w=3.4.

V. EVALUATION AND RESULTS

We now investigate the reliability of the proposed protocol under different network conditions. First we evaluate the performance of the mixed delay and event rates as seen in Table I. In addition we hold this against scenarios with small and large delays to illustrate the optimality of our proposed approach to ensure a reliable aggregator selection.

We look at how the mismatch probability changes by comparing the optimal waiting time found in previous section and different waiting times based on the mean delay time and an arbitrarily chosen waiting time. The delay time, $\bar{D}$ is defined as the average of all mean delays to all aggregators, i.e. $\bar{D} = (1/N)\sum(1/\nu_i)$.

Table II shows the mmPr with the optimal chosen waiting time (T_w=3.4 seconds) from previous section where $\bar{D}$ = 442ms and compare it with waiting time chosen as the double and quadrable mean delay time $T_w = 2\bar{D}$, $T_w = 4\bar{D}$ and an arbitrarily chosen waiting time of T_w =5 seconds.

TABLE II
MMPR FOR EACH AGGREGATOR, FOR THE SCENARIO WITH DIFFERENT DELAYS AND EVENT RATES.

Aggregator	Optimal T_w	$T_w = 2D$	$T_w = 4D$	$T_w = 5$
Aggr. 1	0.04	0.01	0.02	0.06
Aggr. 2	0.17	0.05	0.09	0.24
Aggr. 3	0.14	0.51	0.20	0.20
Aggr. 4	0.11	0.71	0.37	0.06
Aggr. 5	0.15	0.66	0.33	0.16
Avg. mmPr	0.12	0.38	0.20	0.14

Table II shows, the mismatch probabilities for the individual aggregators does not necessarily becomes better. The selected waiting time is in our model based approach trading reliability of the information from aggregator 1 and 2, for reliability of aggregator 3, 4 and 5, which for the delay based heuristics approaches are very costly. In result, the average mmPr for the alternative methods is affected severely as it can be seen.

Although it might be tempting to say that the simplest approach, namely selecting a fixed waiting time of 5 seconds, gives approximately the same result as the optimal waiting time, and does not require any delay estimation. However, due to the missing delay information selecting a fixed time is very sensitive to the actual delays. For example if aggregator 3, 4 and 5 has 100ms delay instead of the ones used shown in Table I, then the model based approach will decrease the average mismatch probabilities to around 3-5 %, while the fixed time will remain at around 15 %, see in Table III.

TABLE III
MMPR FOR EACH AGGREGATOR, FOR THE SCENARIO WITH ALL DELAYS AVG. 100MS AND RANDOM EVENT PROCESS.

Aggregator	Optimal T_w	$T_w = 2D$	$T_w = 4D$	$T_w = 5$
Aggr. 1	0.01	0.41	0.09	0.06
Aggr. 2	0.04	0.41	0.11	0.23
Aggr. 3	0.04	0.41	0.10	0.22
Aggr. 4	0.01	0.41	0.09	0.05
Aggr. 5	0.03	0.41	0.10	0.17
Avg. mmPr	0.03	0.41	0.10	0.15

As an extreme case, if the aggregators had an average delay (this could also include response times from the aggregators and not only network delay) of 2.5 seconds, the difference between the fixed time and optimal becomes 16 percent points as the results shows in Table IV. Further, it shows in this case that the model based approach, gives exactly the same reliability as choosing the quadrable delay.

Similarly, changing the event rates will show that our model based approach provides the best reliability for different scenarios, but results are not shown here due to space limitations.

VI. CONCLUSION

This paper looks at the issue, how to manage energy resource in a smart grid. A specific use case is investigated with Electric Vehicles, as an energy resource, because they are

TABLE IV
MMPR FOR EACH AGGREGATOR, FOR THE SCENARIO WITH ALL DELAYS AVG. 2.5 SEC AND RANDOM EVENT PROCESS.

Aggregator	Optimal T_w	$T_w = 2\bar{D}$	$T_w = 4\bar{D}$	$T_w = 5$
Aggr. 1	0.17	0.42	0.17	0.42
Aggr. 2	0.39	0.46	0.39	0.46
Aggr. 3	0.36	0.45	0.36	0.45
Aggr. 4	0.16	0.42	0.16	0.42
Aggr. 5	0.32	0.44	0.32	0.44
Avg. mmPr	0.28	0.44	0.28	0.44

more dynamic in terms of connecting and disconnecting to the grid. This gives some challenges the control algorithms which have to make use of the energy resource to balance the load on the grid and to the communication network which has to deliver the correct information in time to the control algorithm. A register/de-register protocol has been proposed and a model based approach has been used to analyse the impact of assigning the right aggregator to arriving electric vehicles. Our model based approach allows the Electric Vehicles to be correctly assigned to aggregators with maximum reliability challenged by the information dynamics and current network conditions.

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