Efficient Routing for Overlay Networks in a Smart Grid Context

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Abstract: In the modern smart grid, prosumers and communities, organized in energy collectives, are showing an increased desire to trade energy directly using different forms of decentralized market models. To support local autonomy and distributed services, decentralized networking, using peer-to-peer (P2P) networks, can be used to facilitate dynamic discovery and establish communication between peers. When using a modern overlay network based on a Distributed Hash Table (DHT), the performance of the overlay network can be improved by using the physical properties found in the smart grid context. This paper presents an improved network routing model that takes advantage of these properties, to add a location-aware heuristic to the search algorithms of a standard overlay network. Concepts from complex networks are utilized to improve the average search path and provide a more efficient design over previous solutions. A proof of concept shows that the design results in a more efficient routing model, when used in a smart grid context, compared to a standard uniformly distributed network model.

1 INTRODUCTION

Peer-to-peer networks provides decentralized and distributed communication that can facilitate the dynamic network configuration of distributed energy resources (DER) in a distributed network. Large networks such as consumer broadband and the internet is slow to adapt to changes (Nygren et al., 2010) and do not provide all of the features to support decentralized communication. Overlay networks are developed to provide these features, can be rolled out with a fast cadence, and provides features such as predictable latency (Andersen et al., 2001), scalability, improved robustness and resilience.

The desire from prosumers and energy collectives (Moret and Pinson, 2018) to engage in dynamically changing contract relationships, building micro-grids and operate fully decentralized, requires a communication layer that can handle decentralization and the continuous changes in network topology.An overlay network can provide the solution and facilitate the growth of new services and markets (Greer et al., 2014).

In a smart grid, DERs connected to the grid, have a location property. The location can be static as in the case of stationary DERs or it can be dynamic in the case of electric vehicles (EV). An overlay network is generally based on a uniform distribution of nodes in the network, which ensures robustness and resilience. However the additional properties introduced by the smart grid add both requirements (Budka et al., 2014) to the overlay network as well as the possibility to optimize the distribution of nodes.

The topic of location aware overlay networks and multi-dimensional identifiers has been touched upon by related research, however these works have focused on their specific goals and interests, e.g. the work of (Gross et al., 2013) on searching for peers in a specific geographical location. This paper presents a design of an overlay network that, in a smart grid context, supports using multiple attributes for routing and improves performance over previous solutions. The location property of the smart grid, makes it possible to add location aware routing to the overlay network and use a location-based heuristic to calculate the distance between nodes. To support multi-dimensional routing, concepts from complex network theory is used to structure a routing table that improves routing efficiency.

The overlay network presented in this paper builds

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upon the related work presented in section 2, with the design of an efficient multi-dimensional routing table presented in section 3. A proof of concept is described and tested in section 4 and the results are presented and evaluated in section 5.

2 RELATED WORK

Modern overlay networks are based on a distributed hash table (DHT) (Stoica et al., 2001) which contains nodes with a unique identifier using a uniform distribution of nodes in the network. The identifier is used to calculate the distance between nodes, which is used in the search algorithms. Making overlay networks location-aware has seen several suggestions. One way is to map the multi-dimensional space onto the one-dimensional space of the identifier (Lopes and Baquero, 2007), (Nam and Sussman, 2006), (Zahn et al., 2006), e.g. using space filling curves (Kova et al., 2007), (Chawathe et al., 2005a), (Knoll and Weis, 2006), but it has been shown that it is difficult to do this optimally and it is hard to preserve the original location (Chawathe et al., 2005b). Other designs are based on tree structures that are partitioned into a two dimensional space that maps the two dimensions of a location (Harwood and Tanin, 2003), (Araújo and Rodrigues, 2003), (Asaduzzaman and von Bochmann, 2009), (Heutelbeck and Hemmje, 2006), (Picone et al., 2010). In (Harwood and Tanin, 2003) super-peers are used to control a region and handle load balancing, but these approaches are susceptible to dynamic changes in the network. Another approach is to partition the space into grids (Kantere et al., 2009), but this suffers from poor performance during high churn as well as load balancing issues (Chawathe et al., 2005b).

Kademlia (Maymounkov and Mazieres, 2002) is a well-known overlay network based on a DHT. The basic Kademlia routing table is an unbalanced tree with leafs (known as *k*-buckets) covering a 160 bit address space. Each *k*-bucket covers a part of the range of the 160 bit space and together all the *k*-buckets covers the entire address space in the network. This routing table provides a segmentation of the network and fast lookup. However, encoding multiple dimensions into the 160 bit identifier is not easy without losing the data needed to calculate the distance metric. Replacing the original XOR metric with one based on, e.g., the Haversine distance (Korn, 2000) presents a problem as the address space of the identifier is unknown in a dynamic system. This makes it difficult to efficiently create a *k*-bucket range, or would require continuously restructuring of the *k*-bucket space, resulting in poor performance.

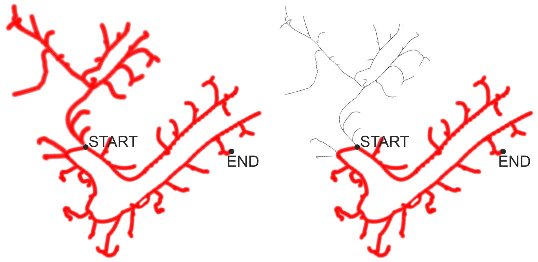
Geodemlia (Gross et al., 2013) proposes a solution to this by creating a small range of buckets which first sorts nodes into buckets depending on their bearing and then into a number of distance-buckets with exponentially increasing distance. However, the width of the address space in the *k*-buckets used in Geodemlia is statically defined, which makes it susceptible to having unbalanced buckets e.g. in the case of heavily clustered nodes within a small area, resulting in a longer search path. Geodemlia add new nodes with a probability inverse proportional to the distance, meaning that it contains more nodes nearby than far away. This fulfills the long-range property (Aberer et al., 2005), but leaves room to optimize the average path length.

Applying small-world network and scale-free network models can improve network performance (Amaral et al., 2000), while the average path length can be reduced by organizing the nodes in a network using the concepts in a small-world network. Watts-Strogatz (Watts and Strogatz, 1998) were some of the first to study small-world networks and describes a model to produce graphs with small-world properties. The Barabasi-Albert model describes an algorithm to generate scale-free network with preferential attachment, which can be used to generate small-world networks (Albert and Barabási, 2002). The Barabasi-Albert model is interesting because it generates networks without the need for a fixed address space. This makes it especially useful for use in a dynamic network growth scenario.

A smart grid can be a highly dynamic system e.g. in the case where EV's move around, resulting in new locations, while properties of the nodes change depending on the applications and services they provide and participate in. The overlay network can be improved over previous solutions by using a heuristic that enables a directed search in the network. Routing efficiency and load balancing can be improved by applying concepts from scale-free and small-world networks, most importantly local clustering, long-range property and random hubs, resulting in an overall shorter average path.

3 ROUTING IN A SMART GRID

The overlay network presented in this section builds on the Kademlia overlay network and uses its protocols and search algorithms. The routing table in the underlying network has been replaced to support location aware routing and search, but can support any number of dimensions. The new routing table is de-



(a) A search using uniform node distribution ripples out from the starting position.

(b) Using a location based heuristic results in directed search and a shorter average path.

Figure 1: Using a heuristic to optimize the search path.

signed to support a multi-dimensional metric and distance calculation.

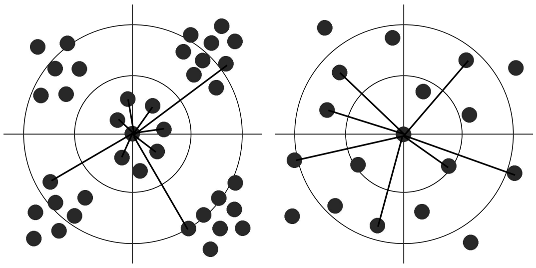
A standard DHT based overlay network uses a uniform distribution of nodes that provides global resilience, load-balancing, good support for churn and many other features. When location is introduced, the distribution becomes clustered around the nodes physical location, this improves local resilience, performance and efficiency, but at the cost of global robustness. To improve global performance, the model and properties of small-world networks is used to improve both local and global performance.

As the underlying routing and iterative search algorithm is based on uniformly distributed nodes, the result is that the search will spread out in all directions as shown on figure 1a. With the additional properties in the smart grid, the search performance is improved by using the location in the heuristic for the distance calculation. The heuristic is based on the geographical distance between the nodes and by directing the search towards the target node, shown on figure 1b, the search path length is reduced.

3.1 Improved Routing Table

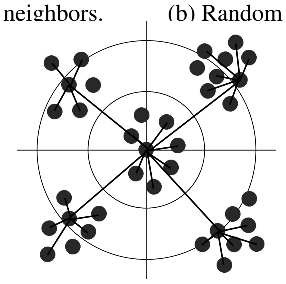
In a small-world network most of the nodes are not neighbors, but there likely exists a connection between the neighbour of a given node and other nodes. A property of small-world networks is that most nodes can be reached with a small number of steps. Another property of small-world network is robustness as the shortest paths between nodes flow through hubs, and if a peripheral node is deleted it is unlikely to interfere with connection between other peripheral nodes. As the amount of peripheral nodes in a small world network is much larger than the amount of hubs, the probability of deleting an important hub node is low.

These properties of the small-world network provides good average performance both when querying



(a) Local neighbors.

(b) Random neighbors.



(c) Random hubs.

Figure 2: Network model concepts used to improve routing efficiency.

local clustered nodes as well as nodes in remote clusters. In a standard overlay network, the identifier assigned to each node is a simple hash value. To provide support for multiple dimensions, a complex identifier is required to contain multiple dimensions, such as a unique id, and coordinates. Because the identifier of the node consist of multiple dimensions, the underlying DHT design with *k*-buckets cannot be used. Instead the design must handle multiple dimensions and do it in a dynamic way, such that the grouping of nodes does not causes hot-spots. Previous solutions uses fixed ranges for the buckets or require continuous recalculation. Preferably the design should adapt to changes in the network by adjusting the bucket ranges over time and in a way that does not require recalculation.

The local nodes in figure 2a ensures detailed knowledge of nearby nodes. This is the most basic bucket of nodes, but needs a dynamic approach that adapts the probability of nodes being added so that it can adjust to different networks automatically. The random neighbors in figure 2b provides the long-range property, which compliments the local nodes by providing access to random remote nodes. The inclusion of random nodes results in a shorter path on average. The random hubs in figure 2c is an additional improvement, where hubs in the network further cut down the average path. A hub is known by many nodes and know many nodes, which compared to random nodes results in fewer network hops. The routing table uses dynamic ranges, such that as the network grows, the routing table dynamically adapts.

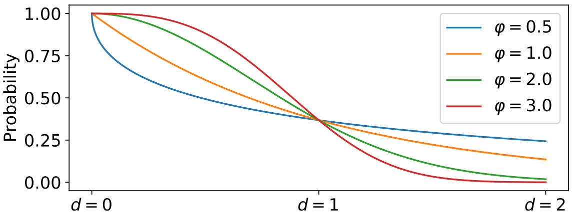


Figure 3: Probability curves for $d_{avg} = 1$. φ affects the probability of nodes being added to A, such that more remote nodes can be allowed or disallowed into A.

The design of the routing table consists of three classes of buckets: A, a dynamic range based bucket of local nodes; B, a bucket containing random nodes; and C, a bucket of network hubs.

The local nodes bucket A, holds the local neighbor nodes and creates a cluster with neighboring nodes such that local nodes have good connectivity. This provides very fast local communication and fast lookup when queried by a remote node.

$$P_a(d) = e^{-(d/d_{avg})^{\varphi}} \tag{1}$$

A has a max size A_{max} of suitable proportions such as 1.000. Nodes are added to A with a probability P_a, shown in equation 1, such that the chance of nodes being added to routing table A decreases exponentially as the distance grows. d denotes the distance to the node, d_{avg} is the average distance of the nodes currently in A and φ describes the slope of the curve, whether it should include more nodes with long distance or with a short distance.

Figure 3 shows the characteristics of probability with changes to φ. The probability curve is dynamically updated as d_{avg} changes with time, as the network grows and the overlay network learns about other nodes. When there are many nearby nodes, the curve will prefer nodes that are even closer and nodes far away have less probability for being added. When there are less nearby neighbors, the algorithm allows for nodes further away to be added. This is an improvement over previous solutions that uses fixed sizes for sub-buckets, which can lead to unbalanced buckets.

Removal of nodes, happens using a FIFO queue, though with a preference for nodes which are inactive, described in equation 2 and 3. When a node becomes inactive e.g. because it is unresponsive or returns bad results, it is placed in a passive queue. As nodes are removed from a bucket, the passive nodes are removed first, and then active nodes are removed, both in FIFO order.

$$n = \begin{cases} L_i[0] & \text{if} \quad L_i \cap Q = \emptyset \\ (L_i \cap Q)[0] & \text{otherwise} \end{cases} \tag{2}$$

$$(L, Q) = \begin{cases} (L \setminus \{n\}, Q\{n\}) & \text{if} \quad n \in Q \\ (L \setminus \{n\}, Q) & \text{otherwise} \end{cases} \tag{3}$$

L denotes the node bucket to remove a node n from, i.e A, B or C, and Q is the queue of passive node.

The random neighbor bucket B, contains nodes which exhibit the long-range property of small-world networks and the distribution is completely random. Nodes with any distance can be added, as statistically, the larger portion of nodes in the network are further away from a given node, than its nearby neighbors and as such, there is no need to cut-off nodes with a short distance. The long-range property is important to provide connectivity to nodes far away and thereby reduce the path length for non-local queries.

$$\text{rate} = r \cdot \frac{1}{t_{last}} + (1 - r) \cdot \text{prev rate} \tag{4}$$

$$P_b = \left(\frac{\text{rate}}{\text{target rate}} \right)^{-1} \tag{5}$$

Nodes are added to and removed randomly from B, operating on a passive modus. I.e. whenever other nodes makes contact, they are added to B. The random property of B is important to keep the robustness of the network, but to avoid excessive rotation of nodes and mitigate abuse or bad behavior, the inclusion of nodes is rate limited. The rate, in equation 4, continually adjusts to reach a target rate. The target rate can be some constant e.g. add max 10 nodes per second or it can be dynamically updated based on network performance or user preference. The rate is based on the previous rate and to help dampen fluctuations, a smoothing factor r is added to the rate. P_b is then calculated based on the rate and the target rate, in equation 5, to provide a probability for adding a new node to the bucket.

The random hubs bucket C, consists of nodes that are estimated to be hubs. As the network grows, some nodes becomes known to many nodes and as such, over time, they become a hub in the network. A node is acquired on an active modus, by actively querying random known nodes for a single random node. This action is scheduled to happen periodically, e.g. on the underlying maintenance loop. New nodes are simply added with no restrictions, as the discovery of new nodes happens in a controlled loop.

When a search is initiated or a query is received from the network, the standard procedure is to compute and return k nodes from the routing table by calculating the distance with a given identifier. In Kademlia the standard specifies that k is 20. Here, using A, B and C a mix of nodes from each is returned

Table 1: Nodes in test networks.

Test network	Number of nodes
European test feeder	900
8500 entity test feeder	2.500
NetworkX geometric network	2.000

to fulfill the properties of a small-world network to form the search set S:

$$S = A\{m\} \cup B\{n\} \cup C\{n\}, k = m+n+n, \quad (6)$$

where the notation $A\{m\}$ indicates that m random nodes are selected from A.

A smaller range from B and C e.g. $n = 5$ is returned and a larger range from A e.g. $m = 10$ is returned. A larger portion of nodes from A is used to increase the probability of returning a local node which may be relevant for the request and to support the underlying algorithm, which has several functions that requires the nearest neighbours of a node. S in equation 6, is sorted according to the distance to the given target node defined in the query and returned to the network query or to the underlying routing algorithm.

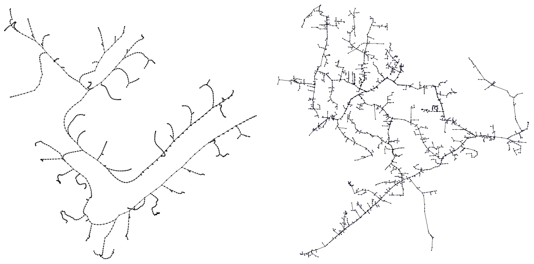
4 PROOF OF CONCEPT

To evaluate the efficiency of the routing table, it was tested in 3 different scenarios. The scenarios consists of networks based on the IEEE European Low Voltage Test Feeder, the IEEE 8500 Entity Test Feeder (Dugan et al., 2009) and a generated geometric scale free network created with the Python library NetworkX (Hagberg et al., 2008).

The routing table design has been implemented in a prototype overlay network along with an implementation of the default Kademlia specification. The two implementations utilizes the same underlying algorithms described by Kademlia.

The IEEE Test Feeder networks, shown in figure 4, provides realistic test cases for testing the location aspect of the heuristic and routing. The test feeders are used both to provide the location data as well as the initialization of the DHT state of the communication links between the nodes in the overlay network. Using the test feeder as a model for a computer network, where every node is more or less chain-linked to only one or two other nodes, results in an unnatural state on initialization for the overlay network. It does however provide a good initialization state for comparing how efficient the routing is able to find its way through the network and to analyze how the routing table is built as it interacts with the network.

Tests are performed using multiple iterations, each with a randomized start point and end points in the network. Each iteration has multiple sub-iterations using the same starting node for the iteration, but with randomized end nodes. This ensures that the network is subjected to queries across more than 90% of the network.



(a) 900 node test feeder layout. (b) 2.500 node test feeder layout.

Figure 4: IEEE Test Feeders.

As each search in the network results in a path that has a different length and because the nodes are randomly chosen, the results cannot be directly compared and needs to be normalized with the shortest path. The shortest path is obtained by utilizing Dijkstra's shortest path algorithm on the full network model, which is used to initialize the network. The resulting efficiency factor ω can be used to compare the tests:

$$\omega = \frac{\text{query path length}}{\text{shortest path}}, \quad (7)$$

where the query path length is the total path traversed in the query including the path count of the sub-queries sent as parallel queries in the algorithm. Note, that ω may be less than 1, as the query path may be shorter than the initial path length after routing table updates.

To simulate an active network, where every node is alive, each node should randomly do some work to exercise its routing table, this will help build the connections between the nodes. To achieve this, a random amount of nodes performs a search in the network for each sub-iteration of the reference node.

4.1 Test Configuration

The test feeder networks are tested with the standard bucket size $k = 20$ and $k = 10$ for the default overlay network and with a range of sizes, noted in table 2, for the multi-dimensional routing table. The purpose is to explore the impact of various bucket sizes. Since a bucket size of 3.000 would equate to a DHT that can contain every node in the European test feeder and about half of the nodes in the 8500 entity test feeder network, it is necessary to test the network using a smaller bucket size to simulate a network where the

DHT can only know a portion of the total nodes. This will make the efficiency of the routing table have an effect as the nodes learns about the network.

Table 2: DHT bucket sizes used for testing.

Overlay network	**Bucket sizes (k)**
Kademlia	3.200 ($k = 20$)
	1.600 ($k = 10$)
Multi-Dimensional	3.000
	300
	150
	60

The size of each bucket: A, B and C in the multi-dimensional routing table is 1/3 of the number in table 2, which means that e.g. A has a size of 1.000.

The NetworkX generated network uses a geometric network model with small-world network properties, to provide an initialization that is similar to a real computer network. This provides a more realistic starting point for testing albeit less realistic with regards to the location aspect.

5 RESULTS

5.1 Efficiency of Routing Tables

The figures 5a, 5b and 5c show the results of running the test on the three different network models. On figure 5 and 6, *md* references the multi-dimensional routing table and *kd* references the standard Kademlia routing table. The dotted lines are the results of the default overlay routing based on Kademlia with standard bucket size and also $k = 10$. The other lines shows the multi-dimensional routing table using the four different bucket sizes. The curve is very steep in the first few iterations, as the overlay networks learn about the nodes in the network. Because the nodes are initialized with a very simple state, the first queries in the network will fill up the routing tables quickly. The results on figure 6 show the average bucket size across the entire network for each iteration. The connection between the efficiency on figure 5 and the bucket size shows that, as the buckets are filled, the efficiency improves. Generally the standard routing table is filled faster than the multi-dimensional routing table, this is partly because the standard routing table performs more queries in the network and partly because of the configuration of the probability curves for the multi-dimensional routing table. A continuous increase in performance on figure 5 can be seen from the graphs as the properties from small-world networks begins to have an effect. The Kademlia curve reaches a plateau, where it doesn't really improve any further with the given network. But the multi-dimensional routing table continually improves its efficiency as it is able to bring down the average path length by taking advantage of the long-range and random hub properties.

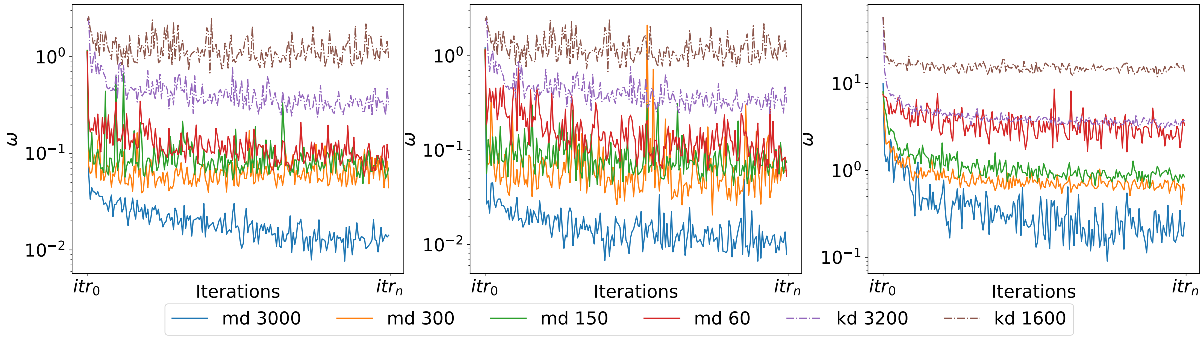
The difference in efficiency, using different bucket sizes becomes visible in two different ways: first the initial learning curve lands on different levels, where the size of the bucket dictates the efficiency level, a larger bucket can hold more nodes giving a larger knowledge space. The second way is less obvious, in the test feeder networks, the smaller buckets actually converges to about the same efficiency, but still with an improving trend. However, using too small a bucket size hinders increase in efficiency as the bucket will start forgetting nodes. The overall efficiency increase across all three networks is about a factor 10. A good solution has both a small ω and a small bucket size. The less space used, the more optimal the solution is.

5.2 Discussion

In the presented routing table, an issue arises, when the algorithm has to move in a direction that goes against the heuristic. Since the heuristic prefers to move towards the target node location, it tends to examine the nodes in that direction first, but if the only connection to the node is through a node that lies further away than the given start node, it will prefer to not take that route. This is where the random neighbor and random hubs are important, as they allow the algorithm to try a search starting from a different point in the network. This not only allows the search to succeed, it also improves the average path length.

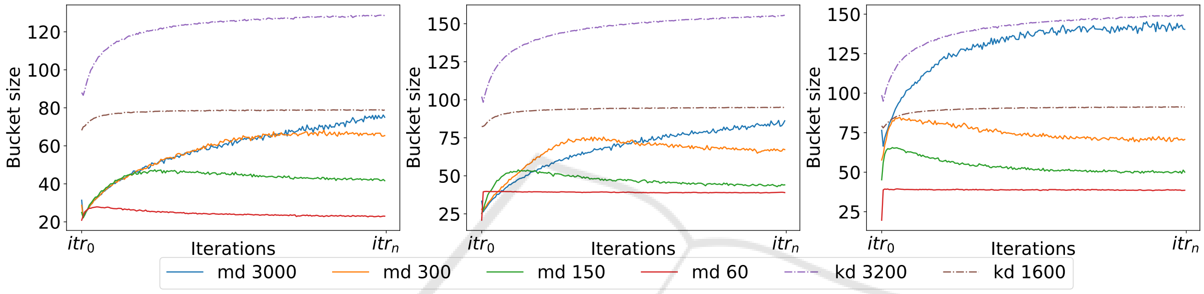
To improve network stability and to provide some protection against attacks like denial of service (Douceur, 2002), additional properties may be tied to the nodes to affect whether a node should be kept in the routing table or removed. These properties could range from long-lived nodes, query round-trip time, bandwidth, load-balancing indicator etc. Adding a latency property to the routing would enable the algorithm to find the path with the lowest congestion.

Churn, i.e. nodes entering and leaving the overlay network, is an inherent and significant property of overlay networks (Stutzbach and Rejaie, 2006). In our work, it was not necessary to test churn, as the focus was on location based heuristics and establishing an efficient routing table. The simulated systems were based on power grids, where the unit state, based on location, updates rarely. Applying the small-world network model is something that can improve routing during churn, e.g. if a node leaving has blocked the path to a target node, the small-world network is able



(a) ω: 900 node test feeder. (b) ω: 2.500 node test feeder. (c) ω: NetworkX geometric generated network.

Figure 5: Routing efficiency results for IEEE test feeders and NetworkX generated network.



(a) Bucket size: 900 node test feeder. (b) Bucket size: 2.500 node test feeder. (c) Bucket size: NetworkX geometric generated network.

Figure 6: Average bucket size calculated from every node in the network on each iteration.

to find a new route with a shorter search path on average, than the underlying routing, which may have to start a search that fans out in every direction again.

Using a complex identifier comes with a cost. Most importantly the computing cost goes up as more properties are added to the identifier. The distance calculation is performed multiple times for each node in the routing algorithm. When another property is added, that increases the cost and more so if the calculation is complex. The cost of the distance calculation for the Pythagorean location is very small and the increased efficiency of the heuristic far outweighs the cost in the scenarios tested here.

6 CONCLUSIONS

With the desire of prosumers and energy collectives to trade energy directly and increasing autonomy at the local level, overlay networks can provide the required decentralized communication. The multi-dimensional overlay network presented in this paper was shown to utilize the properties in the smart grid to provide a heuristic based on location that improved routing efficiency and using the concepts from complex networks both averted the inherent problems with robustness in a clustered node distribution and improved the average path length when searching in the network. The results showed a increase in performance over the standard Kademlia overlay network in the context of a smart grid.

In future work, churn is going to an interesting parameter to test when the unit state is based on system dynamics that changes rapidly. The default storage algorithm causes hot-spots with clustered nodes and load-balancing needs to handled and measured. Both the small-world properties and the location based heuristic improved efficiency, however testing the small-world properties with the heuristic enabled and disabled would provide additional valuable insight.

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