A Scalable Geographic Routing Protocol for Virtual Power Plant Communications

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***Abstract*—ICT is an enabling technology for the integration of distributed energy resources and storage (DERS) within the power grid as well as implementation for innovative services such as demand side management (DSM) and demand response (DR). Nevertheless, individual DERS are too small to be allowed access to energy market, likewise utilities are unable to effectively control and manage small DERS. Virtual power plants are a concept, that can solve this sparsity problem, they attempt to aggregate DERS to present them to the rest of the power grid as a unique technical and/or commercial entity. This contribution deals with ICT for the VPPs. It presents a novel geographic routing protocol that is able to support different control strategies for the VPPs and accommodate their dynamic structure with seamless enrollment and dis-enrollment of prosumers.**

***Keywords*—smart grid - Virtual power plant - Wireless sensor network - peer-to-peer communication - routing protocol - geographic routing**

I. Introduction

Conventional electrical grid consists of large, often remote, centralized power plants that feed power over radial or mesh grids to end users using uni-directional power flows. The scarcity and the expensive cost of conventional power sources along with renewable energy subsidies and environmental concern fostered the move to smart grids with bidirectional power flows that accommodate distributed generation (DG). Henceforth, new actors are born in the power grid, prosumers, which are new end users that can produce, consume and store energy.

Virtual power plants are related to these new actors. They attempt to aggregate prosumers' DERS to present them to the rest of the power grid as a unique technical and/or commercial entity. In fact, the integration of DERSs into the grid, in particular renewable energy sources or natural storage, would certainly enable a sustainable energy system with less environmental concerns, more diversified energy resources and enhanced energy efficiency. However, DERS units working isolated due to their different ownerships may help satisfy local needs for a house, a building or a business but their integration within grid could rapidly become a headache for utilities and DSOs for their influence on grid's stability, voltage, power factor, etc.

A VPP is a set of geographically sparse Distributed Energy Resources (DERs) including power generators, controllable loads and storages that are aggregated in a way to perform as a single power facility.

From a technical perspective, the VPP tries to optimize control and coordination, as well as system operation. It interacts directly with the Distribution System Opertator (DSO) providing him with a unique profile of the whole aggregated plant to assist with network management and provide ancillary services. From an economical point of view, VPP describes an economic aggregation of geographically sparse industrial, commercial and residential generation and consumption assets into a single business entity. It integrates Demand Response (DR) programs and demand side management in order to trade the produced energy and or shedded load to the best of the owners interest. Hence, the VPP directly interacts with the energy market.

Control of VPPs could be centralized, descentralized and fully distributed. In the centralized control [1] all the knowledge about the DERs production and the energy market is located in the central controller. This gives the VPP a simple way of using DERs to meet grid demand. However, different ownership, and the large number of DERs within a VPP challenge the central controller find optimal control strategy to respond to best prosumers interest.

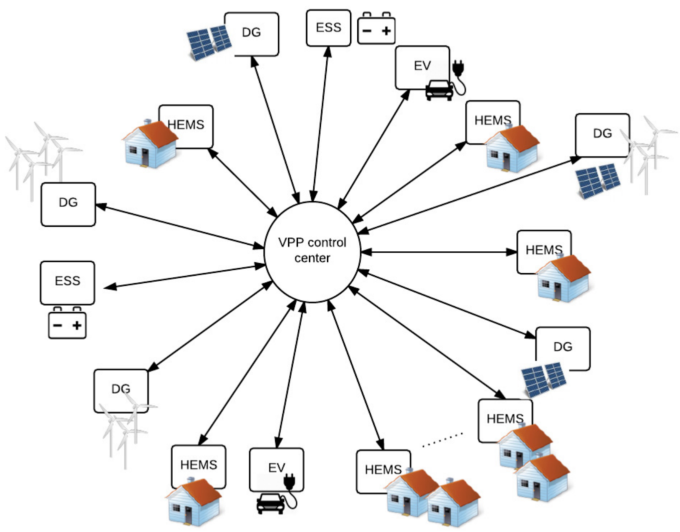


Fig. 1: Centralized controlled VPP

In the descentralized control, the complexity is divided vertically within the VPP. [2] introduces a hierarchical model by defining VPPs on different levels. A local VPP supervises and coordinates a limited number of DERs while delegating certain decisions upwards to a higher level VPP. This design requires communication between different neighboring VPPs.

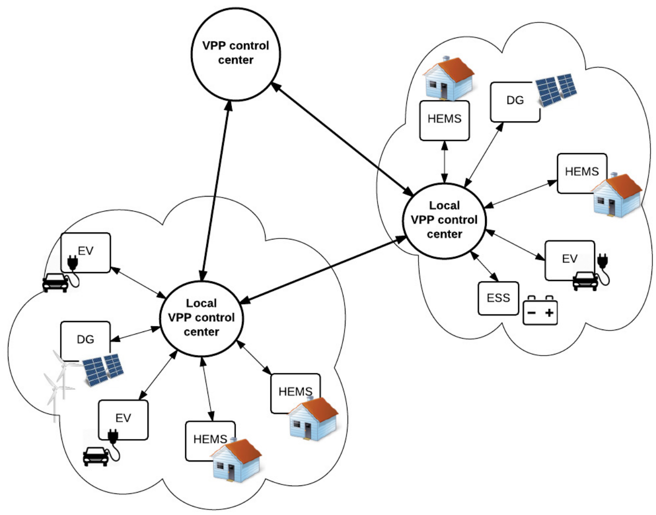


Fig. 2: Distributed controlled VPP: hierarchical model

In the fully distributed control, each DER has communication and processing provisions to participate (and react) independently and smartly in (to) the state of the power system. An example of such control is reported in [3] where minimal coordination between neighboring DERs is reported to be enough to reach global optimum state for the whole VPP.

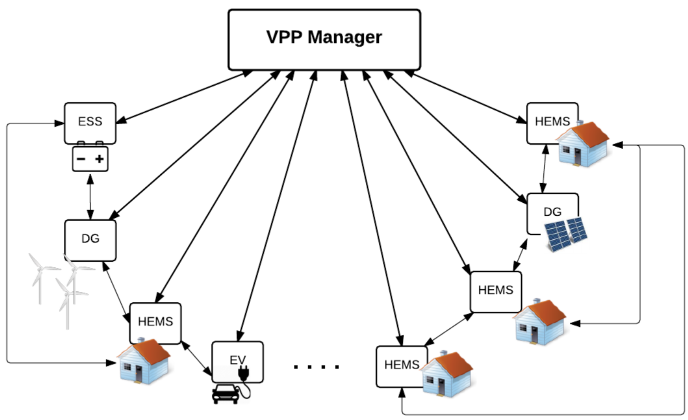


Fig. 3: Fully distributed controlled VPP

The development of VPP integrating DERSs, DSM and DR relies on the implementation of Advanced Metering Infrastructure (AMI), Information and Communication Technologies (ICTs) and Network Automation [2]. AMI permits bidirectional flow of information between consumers, providers and grid devices part of the VPP such as smart meters and sensor-based controllers of power system equipment. On the other hand, the adherence of prosumers to a VPP is optional, therefore, VPPs are dynamic and should accommodate a plug and play mode of enrollment or dis-enrollment of prosumers. Besides, a VPP could start with a limited number of DERSs to rapidly scale to thousands of prosumers. Moreover, coordination between DERSs for number of ancillary services is critical for higher integration of DERSs within a powergrid [4]. Thus, decentralized control or fully distributed control hold much promise regarding managing a dynamic VPP.
The deployment of intelligent devices and a convenient ICT contribute to a reliable and secure communication scheme for exchanging data between concerned entities involved in efficient distributed control within VPPs and the different associated services. The adopted solutions should be scalable, memoryless, rapidly deployable and capable of point to multi point, multi point to point and peer to peer communication between DERs to allow for flexible smart distributed control schemes.

The main contribution of this work, is the development of a novel geographic routing protocol for neighborhood area network (NAN) part of the smart grid that supports all modes of communications required for VPPs. In the next section we review some of the existing routing protocols for NANs and compare them related to the supported communication modes, their reliability and their complexity. Then we introduce a new routing protocol that can be used for communications for the NAN. Finally, simulation results are presented for different NAN densities.

II. Routing protocols for SG NAN

Many routing protocols have been proposed to be used for communications within the NAN in smart grid:
The Ad-hoc On-demand Distance Vector (AODV) protocol [5] is a reactive routing protocol that uses flooded route request messages to discover paths to destinations on demand. [6] proposes an improved AODV (IPODV) routing that ensures an efficient data transmission. Although IPODV produces more robust routes than in AODV while using less control packets, the cost of creating routes remains high which may affect the performance of the network.
Distributed Autonomous Depth-First Routing (DADR) [7] is a multipath routing algorithm for wireless mesh networks. It uses a lightweight control mechanism to provide at most k possible paths for each destination in addition to a backtracking mechanism for path recovery after link failures. Simulations of DADR in large scale networks proved its scalability and that it creates less control overhead compared to AODV and Optimized Link State Routing (OLSR) [8] for path recovery after link failures.Although, DADR adapts quickly to the frequently changing topology, its recovery mechanism adds additional state in the data forwarding phase which increase the CPU and memory overhead of intermediate nodes. Another disadvantage is the packet latency.
Hybrid Routing Protocol (Hydro) [9] is a multipath link-state routing protocol for Low-power and Lossy Networks(L2N). It utilizes Directed Acyclic Graph (DAG) to provide multiple paths from in-network nodes to a border router. The DAG provided point-to-point (P2P) routing by allowing nodes to forward packets to a border router, which in turn routes them to the appropriate destination. In order to improve the reliability of the created paths, the border router maintain a global view of the network topology by aggregating topology

reports periodically created and sent by each node in the network. Hydro is a reliable routing algorithm that supports central control traffic (multipoints-to-point (MP2P) and point-to-multipoints (P2MP)), however, its support for P2P traffic is basic, and results using longer routes and thus bigger delays. Besides, the creation of the DAG and the periodic reporting may surcharge the network with the control packets and create significant overhead specially in large scale networks.

IEEE 802.11s routing [10] is a multi-hop Wireless Mesh Networks (WMNs) extension of the IEEE Standard 802.11. The Hybrid Wireless Mesh Protocol (HWMP) is used as the default path selection protocol for IEEE 802.11s routing. HWMP is a hybrid tree routing realized by combining two types of routing protocols: on-demand routing protocol and tree-based proactive routing protocol. The proactive protocol is used to maintain routing state. However, the on-demand routing, also called reactive routing, is used to eliminate the impact of frequent changes of network topology and it enables P2P communications between two nodes. IEEE 802.11s operates on the same PHY layer as 802.11 based standards, so that data transmission will be in a high-speed mode, which is different from IEEE 802.15.4g which makes it a potential candidate for reliable and high-speed wireless NANs applications[11]. The main drawback of HWMP is routes instability [12]. Besides, a lot of information need to be maintained at the nodes which increases the complexity thus affect the nodes lifetime [11]. Several improved version of IEEE 802.11s routing have been proposed in the literature to meet with smart grid requirements [12][13][14].

RPL [15] is a routing protocol for Low power and Lossy Networks (LLNs) designed by the IETF Routing Over Low power and Lossy networks (ROLL) Working Group. It consists of maintaining network state information using one or more DAGs. The RPL is optimized for MP2P and P2MP communication schemes [16]. For that reason, it was proposed as a routing solution for AMI networks [17][18] where traffic is limited from meters to a concentrator, and from a concentrator to meters. In this context, different implementations of RPL routing protocol have been proposed in the literature to meet with NAN requirements. The authors of [19] proposed a routing algorithm based on Multiple RPL instances with QoS differentiation at network layer in order to account for NAN's applications requirements. In [20], a modified version of RPL is proposed to support multi-gateway AMI network case. In fact, the standard RPL defines an RPL instance with different disjoint DAGs, each one corresponding a root. For that, the multi-gateway RPL allow a node to join multiple DAGs in order to increase viable routing options [20]. CORPL [21] is another proposed RPL variant for the context of AMI networks, it addresses the problem of unstable wireless links and interference effects. RPL provides only basic support for point-to-point traffic [18]. When a node sends a packet to another node, the packet uses upward route until arriving to a common ancestor at which point it is forwarded in the downward direction to the destination.

Some QoS routing protocols have been proposed for NAN. A multi-constrained QoS routing protocol, called Optimized Multi-Constrained Routing (OMCR) is proposed in [22]. OMCR is a simple greedy algorithm based on two QoS requirements: delay and outage probability. [23] introduces Q-HWMP that is an imporved HWMP protocol that handles QoS for real time applications.

Since the nodes are static and their location is known a priori, several geographic routing protocols have been proposed for NANs. [24] introduces an adapted WSN geographic routing for PLC. Beacon-less Routing (BLR) [25], Beacon Based Routing (BBR) [26], and Implicit Geographic Forwarding (IGF) [27] are examined. The Greedy Perimeter Stateless Routing (GPSR) [28] was considered as a strong candidate for routing in SG, in particular in NAN [29]. GPSR is a geographic routing that guarantees data delivery. Several studies compared the performance of GPSR and RPL [30][31][32], simulations show that RPL outperforms GPSR in terms of end-to-end delay and reliability.

Most of these protocols provide MP2P and P2MP routing capabilities, some of them propose extensions for P2P communication support that are not optimized. The reliability is achieved at the expense of higher complexity or greater overhead or extended end to end delay.

III. Geographic **GR**eedy routing with **ACO** based recovery (**GRACO**)

A. Geographic routing for VPP communications

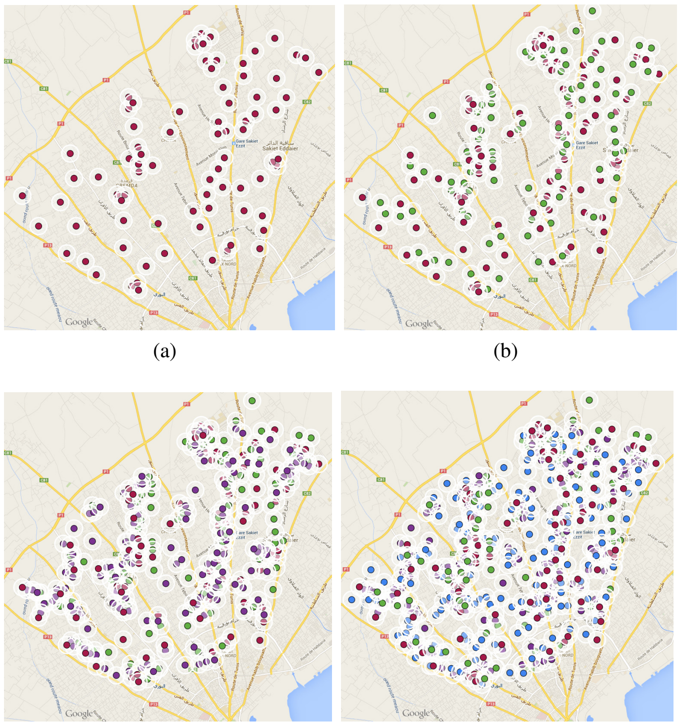
The Geographic Routing is a class of routing protocols that use the geographic position of a node and its immediate neighbors to route traffic. These protocols are fully distributed and localized routing schemes. Every node performs the same algorithm, packet forwarding decision is achieved using only information about its own position, the position of the destination node and the positions of nodes available in the vicinity at the time of the routing request. this reduces the communication overhead needed for path construction. Moreover, GR protocols are scalable and memory-less since there's no need to memorize information neither on the nodes within a path, nor in the data packet [33].

The geographic locations of the different entities of a virtual power plant are well known to the VPP manager. It's, therefore, intuitive to exploit this knowledge when routing data for communications within the VPP. Besides, the GR localized and the fully distributed working allows for communication of any node to any other node within the VPP in a peer to peer scheme. Moreover, these protocols scalability and memory-less features accommodate well the highly dynamic topology of VPPs related to their expansion with enrollment of new nodes or to the harsh communication environment within urban regions or such.

Many researchers investigated the use of geographic routing for AMI networks. [28] proposed the use of Geographic Perimeter Stateless Routing(GPSR)in this context. [30] studied the feasability and the performance of GPSR in NAN scenarios. It was proved that GPSR can support different NAN services in terms of latency and reliability. In [31], the authors compared the performances of GPSR to RPL in the case of NAN network. The simulation results proved that RPL outperforms GPSR in terms of transmission reliability and delay. However, the RPL offers only limited support to P2P communications [18] which makes it not suitable for distributed control strategies that require communication between neighbor nodes.

B. Overview of GRACO

GRACO [34] is a geographic routing algorithm that combines a pheromone-assisted greedy forwarding mode and an Ant Colony Optimization (ACO) based recovery mode. In the beginning, GRACO makes the routing decision using geographic greedy forwarding strategy [33]. Greedy forwarding is the simplest implementation of geographic routing. At each step, a node tries to bring the packet closer to the destination, using the euclidean distance as a the progress criteria. Greedy forwarding inherits all the advantages of GR. However it is not always possible, it may lead to a void problem if a packet arrives to a node that has no neighbor closer to destination than itself, the node is, then, stuck and could not progress the packet. GRACO proposes an ACO based strategy to recover from the void problem. The ACO recovery strategy uses two types of ant like packets: Fants to search for a path around the void and Bants to mark the paths found for later use. The Fants will be guided to the direction of the destination using zone concept. Once a Fant arrives to an unstuck node, a node closer to the destination than the stuck node, a Bant is sent to mark the path found by dropping pheromone trails. The recovery is launched with the aim of finding an unstuck node, then, the algorithm switches to greedy forwarding again. The performance of GRACO was compared to the greedy-face-greedy (GFG) routing algorithm. Simulations results presented in [34], shows that GRACO outperforms GFG in term of end-to-end delay, data delivery cost and hop count. Besides, GRACO provides a high data delivery rate.



(a) (b) (c) (d)

Fig. 4: Stages of VPP extension within an urban region

IV. Simulations and Results

The performance of GRACO is measured using the WSNET simulator [35].

The simulations are performed within an urban region presented in figure 4. We choose to incrementally add nodes to the VPP in order to simulate the evolution of the VPP from early stages of a VPP where just a few customers are enrolled in the VPP and the DRs are sparse across the selected region to more advanced stages with denser aggregation of DERs representing a more mature version of the VPP where an important number of prosumers has been attracted by the financial benefits of the DR programs.

To vary the nodes degree, we vary their range from 25m to 50m by steps of 5m. Each combination of topology and algorithm is run 50 times. Error bars on curves symbolize a 95% confidence interval. In order to measure the impact of void zones on the

Parameter	Value
Duration (s)	300
MAC layer	802.15.4
Interferences	none
Density	10, 15, 20, 25, 30, 40

TABLE I: Simulation parameters

algorithm performances, we choose a set of random sources and destinations where there is, necessary, a void to be handled in the routing process. One data packet is sent between a pair of source and destination each 10s.

The performance of the routing protocol is measured in terms of the average route length, the end-to-end delay and the data delivery ratio. The route length is the number of hops a data message needs to go from the source to destination. The end-to-end delay is the time interval between a given source sends a packet and the destination receives it. The delivery ratio is the ratio of data packets successfully received by their destinations to all data packets sent by the sources. Table I summarizes the simulation parameters.

The simulation results show that the more the network is dense the better performs the proposed routing protocol.

As the density of the network is increased, shorter paths are found. Specifically, as plotted in figure 5, the average route length drops from 37 hops at network density 10 down to 16.32 hops at network density 40.

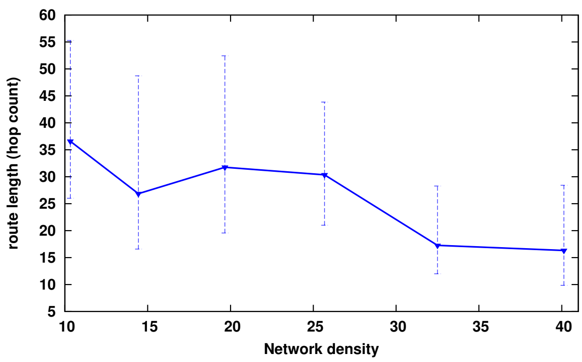


Fig. 5: Hop count

Figure 6 shows the end-to-end delay varying with the network

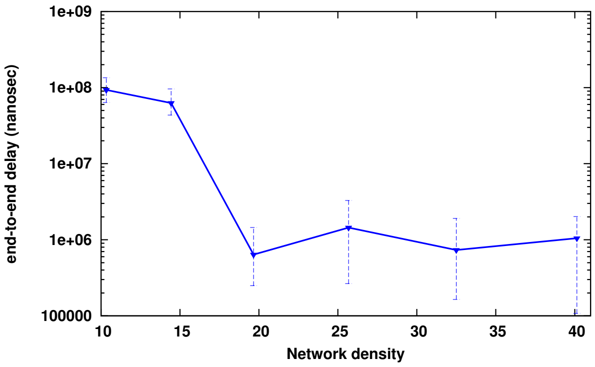


Fig. 6: end-to-end delay

density. The average end-to-end delay reduces from 93,183 ms at a network density 10 to 1,049 ms at a network density 40.

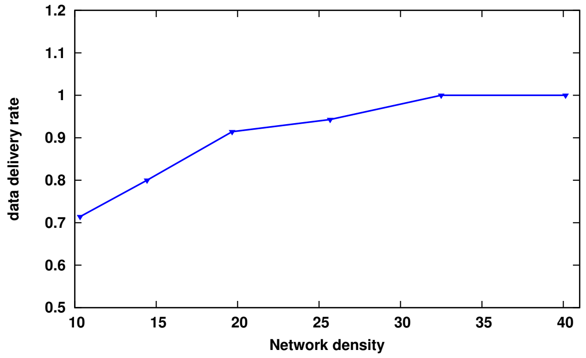


Fig. 7: Data delivery rate

The data delivery rate is also improved when increasing network density, as presented in figure 7, it is improved from 71.4% at a network density 10 to 100% s at a network density 32. Thus, for 802.15.4 mac layer, a 100% delivery rate is achieved in a high density network.

V. Conclusion

A wireless sensor network is proposed to facilitate installation and development of dynamic virtual power plant. the proposed ACO aided geographic is scalable and ensures point to point communication allowing for versatile control strategies for the VPP such as fully distributed control to overcome the challenges of centralized control. Delivery rate are within the VPP communication requirements. End-to-end delay decreases with increasing network density or VPP size. This is consistent with the need for larger DERs communication traffic within neighborhood for best control strategies decision.

VI. Acknowledgments

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