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Geographic Routing Protocol for Peer-to-Peer Smart Grid Neighborhood Area Network

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***Abstract*—The distribution segment of the power system is of great importance in the smart grid (SG). The deployment of ICT to support conventional grid will solve legacy problems that used to prevent implementation of smart services such as smart metering, demand side management or the integration of Distributed Energy Resources (DERs) within the smart grid. In this contribution, GRACO, a new geographic routing algorithm is proposed to support exploitation of SG full potential. We demonstrate, through simulations,the effectiveness of GRACO in terms of scalability, peer-to-peer routing, end-to-end delay and delivery rate.**

***Keywords*—smart grid - Neighborhood Area Network - Wireless sensor network - peer-to-peer communication - routing protocol - geographic routing**

Acronyms and Abbreviations

SG	Smart Grid
DER	Distributed Energy Ressource
ICT	Information and Communication Technology
DSM	Demand-side management
DA	distribution automation
SGCN	Smart Grid communication network
HAN	Home Area Network
NAN	Neighborhood Area Network
WAN	Wide Area Network
AMI	Advanced Metering Infrastructure
FAN	Field area network
IETF	Internet Engineering Task Force
LLN	Low power and Lossy Network
ROLL	Routing Over Low power and Lossy networks
RPL	Routing Power for Low power and Lossy network
DAG	Directed Acyclic Graph
GRACO	geographic GReedy routing with ACO based recovery

I. Introduction

Conventional electrical grid consists of large, centralized power plants that feed power over a grid to end users using one-directional power flows. The Smart Grid (SG) is the expansion of the traditional electrical grid with the integration of Distributed Energy Resources (DERs) and Information and Communication Technologies (ICTs), to better meet the increasing energy demand and environmental regulations.

SG offers a set of services that allow utilities to a more intelligent an efficient management of the system such as smart metering, demand side management, the integration of DERs, distribution automation, etc.

Demand-side management (DSM) is a service that aims to ensure stability on the electricity grid. In fact, instead of adding more expensive generation to the system, DSM aims to maintain electricity supply and demand in balance in real time. It consists of a set of programs and activities designed to allow and encourage consumer to modify their electricity usage habits in order to reduce their consumption during peak periods. DSM comprise demand response (DR) programs and energy efficiency and conservation programs [1]. DR, called also load shifting, consists of transferring customer load during period of high demand to off-peak periods. Energy conservation programs encourage customers to give up some energy use in return for saving money, for example, turning up the thermostat a few degrees in summer to reduce air conditioning. On the other hand, Energy efficiency programs allow customers to use less energy while receiving the same level of end-service , such as replacing old electrical device with a more energy efficient one.

One of the promises of the Smart Grid is better and more uniform integration of distributed energy resources (DER) into the grid, in particular renewable energy sources [2]. Indeed, the integration of DERs into the power grid enable a sustainable energy system with less environmental problems, more diversified energy resources and enhanced energy efficiency. However, DER units working isolated due to their different ownerships may help to satisfy local needs but not the whole grid. Thus, cooperation and communication is a key factor in the integration of DER into the grid.

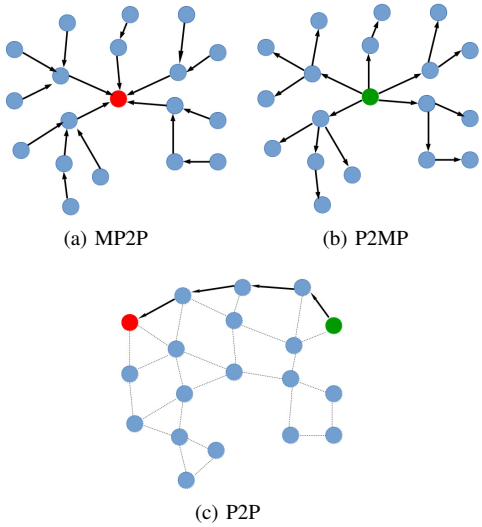
With the integration of such services into the smart grid, the centralized control is no longer effective. The fact that every device communicates with central controller before making a decision or communicating with other device in the network will affect the efficiency of the system by adding extra delays and flooding the communication network with extra transmitted data packets. Thus, a distributed control is required for a smart and efficient management.

A decentralized distributed system consists of multiple intelligent software entities, called agents, working together via parallel and distributed processing to solve a complex problem. In distributed controlled SG, the agents, distributed all over the electric grid, and each is responsible of the control of a specific physical system, are interconnected via an heterogeneous communication network [3]. In such system, devices will communicate with each other without a central monitoring using peer-to-peer communication. There are many applications of distributed applications in power systems such as reactive power compensation, distributed control of DERSs, distributed aggregation of smart metering data, autonomous fault detection and reconfiguration, etc. The deployment of intelligent devices and a reliable and secure peer-to-peer communication scheme for exchanging data between concerned entities enables an efficient distributed control.

In the present work, we propose the use of geographic routing for data transmission in peer-to-peer communication in NAN. We studied the performance of a new geographic routing protocol called GRACO in different networks densities.
In the next section, we define peer-to-peer communication scheme. Then we introduce NAN. This will allow us to highlight communication needs for the NAN. In section IV, we report a routing protocol for low power and lossy networks (RPL). This protocol has been standardized by The Internet Engineering Task Force (IETF) and is intended for wide variety of applications including home automation, urban sensor networks and AMI systems [4]. We overview the RPL protocol with the objective of pointing limitations that can hinder its application in a distributed control NAN. Then we propose a new routing protocol that can be used for communications for the NAN. Finally, simulation results are presented for different NAN densities.

II. Peer-to-Peer communication scheme

Peer-To-Peer (P2P) communication, also called Device-To-Device (D2D), Point-To-Point and Machine-to-Machine (M2M) communication, is a communication scheme in which every device in the network is able to directly communicate with another device without a central control. In Point-to-Multipoint (P2MP) and Multipoint-to-Point (MP2P) networks, the communication is based on a master/slave relationship, in fact, in P2MP, one source node can transmit packets to many nodes, and in MP2P, one destination node can receive information transmitted by many nodes. Unlike P2MP and P2MP, in P2P, it is not necessary that all the nodes are connected to the central node. Furthermore, a network using P2P communication scheme is a robust and scalable network.

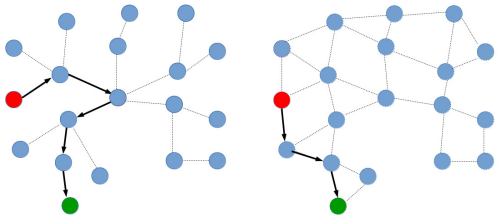


(a) MP2P (b) P2MP

(c) P2P

Fig. 1: communication schemes

P2P networking has been investigated by the research community as a viable and effective approach to ensure scalability, self-organization and resiliency to the telecommunication infrastructure of smart grids [5]. Using a P2P scheme, a data packet forwarded will use a shorter path than the one used in a central control based topology. Besides, flooding one central node with huge traffic will increase significantly transmission delay and may also affect the reliability of the nerwork. For these reasons, the P2P communication in distributed control systems is expected to reduce the transmission delay.



(a) P2P in center based topology (b) P2P communication

Fig. 2: example

On the other hand, the power grid is a delay-sensitive system, it has strict delay requirements since a delayed message can cause potential system failures. For example, a fault event message need to be delivered within maximum 3s, in order to isolate the affected segment, otherwise the whole system will be damaged. Hence, due to its high-reliability and time-critical requirements, P2P communication scheme is a sweetable networking solution for smart grid applications.

III. Neighborhood Area Network

The communication layer is one of the key elements to enable smart grid applications. SG communication network (SGCN) is divided into 3 networks based on the coverage range and data rate: Customer premises area network or Home Area Network (HAN), Neighborhood Area Networks (NAN) and Wide Area Network (WAN).
NAN ensures communication in the distribution grid. It is composed of Advanced Metering Infrastructure (AMI) and Field area network (FAN). The AMI provides a two way meter-utility communication in order to collect, measure, and analyze energy consumption data for grid management, outage notification, and billing purposes [2]. On the other hand, the FAN ensures communication between field area devices and the control center. It enables a set of applications in the distribution level such as advanced Distribution Automation (DA) (Fast fault location, recovery, Conservation Voltage Regulation, Volt/Var control; Power Quality controls; etc). Distribution automation (DA) allows utilities to remotely monitor and control assets in its distribution network through automated decision-making, providing more effective fault detection and power restoration [2].
The NAN is modelled as large scale network composed of a big number of wireless nodes (meters, sensors, field area devices, gateway). Although NAN nodes are immobile, the quality of wireless links between two nodes can be unstable due to fading and signal interference [6]. Therefore, a routing solution for NAN must be self-healing by providing a rapid recovery strategy with minimum control. Applications supported by NAN are delay sensitive. Thus, a routing solution for NAN must be reliable in terms of packet delivery rate and end-to-end delay. The adopted solution should also be scalable,

and rapidly deployable in order to support the continuing enrollment of new participants.

IV. Routing Protocol for Low Power and Lossy Networks (RPL)

RPL [7] 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.
RPL consists of maintaining network state information using one or more Directed Acyclic Graphs (DAGs) [8]. A DAG is a directed graph wherein all edges are oriented in such way that no cycle exists [9]. Each DAG has a root node and client nodes. A rank, calculated using an objective function, is assigned to each client node in the DAG. The rank monotonically increases in the downward direction so the root has the lowest rank. The objective function is defined using various link and node metrics and constraints to compute the best path.
To create a DAG, RPL uses a set of ICMPv6 messages to exchange graph information. The DAG creation starts by the root sending a control packet called DIO (DAG Information Object packet). A DIO message contains information about the DAG such as the DAGID used to identify the DAG as sourced from the DAG root; rank information used by nodes to determine their positions in the DAG relative to each other; objective function identified by an Objective Code Point (OCP) that specifies the metrics used within the DAG and the method for computing DAG rank.
If a client node receives a DIO message and decides to join the DAG, it should add the DIO sender (the previous node traversed by the DIO) to its parent list, compute its own rank (associated with the parent node) Based on information carried in the message (OCP) ant its local state, and broadcast the DIO message with the updated rank information.
In case of loosing connectivity, a node will send out a DAG Information Solicitation (DIS) message and the neighboring nodes that hear it will respond with a DIO message announcing they are a part of a DAG.
Using the constructed DAG, each client node will be able to forward any upward traffic (an upward traffic is a traffic destined to the DAG root) through its parent as the next-hop node.
To create downward routes from the root to a client node, the client node should issue a control message called Destination Advertisement Object (DAO). A DAO packet includes the rank information used by nodes to determine how far away is the destination (in this case the destinations is the client node). The DAO message will be forwarded to the root using the upward path indicated by the DAG, and all the intermediate nodes record the reverse path information from the DAO message, after that, a complete downward path is established from the root to the client node.
The RPL is optimized for multipoints-to-point and point-to-multipoints communication schemes [10]. For that reason, it was proposed as a routing solution for AMI networks [8][11] where traffic is limited from meters to a concentrator, and from a concentrator to meters. In this context, different implementations (variants) of RPL routing protocol have been proposed in the literature to meet with NAN requirements. The authors of [12] 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 [13], 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 [13]. CORPL [9] is another proposed RPL variant for the context of AMI networks, it addresses the problem of instable wireless links and interference effects.
RPL provides only basic support for point-to-point traffic [11]. 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.
To conclude, RPL provides an efficient support of dynamic routing metrics and constraints required by the AMI network. However, establishing and maintaining efficient upward and downward routes according to each possible root can result high overhead specially for large scale networks which may affect the reliability and scalability of the routing solution. Besides, RPL does not provide an optimized point-to-point traffic support. For these reasons, RPL is not suitable for P2P NAN. In the next session, we will propose the use of geographic routing for P2P NAN.

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

A. Geographic routing for large scale P2P NAN

Geographic routing (GR) is a class of routing approaches that exploit geographic position in routing decision in stead of topological information. It has been widely used in ad-hoc and wireless sensor networks for its diverse advantages. In fact, GR is a localized routing scheme since packet forwarding decision is achieved by using only information about the position of nodes in the vicinity and the position of the destination node, which minimizes significantly communication overhead. Hence, no additional information has to be stored neither on the nodes on the path, nor in the message which makes GR a memory-less and scalable routing [14]. Besides, GR is also distributed, every node performs the same algorithm [14]
As previously discussed, the deployment of a wireless communication network for the NAN faces many challenges. First of all, NAN is supposed to support different applications and multiple traffic flows, the communication network should then manage a huge amount of data, thus, the routing solution should deliver the data packets with the minimum overhead possible so it does not affect the network performances. As NAN is a large scale network with highly dynamic topology due to the often expansions to cover larger areas and additional endpoints, it needs a scalable routing solution. Besides, the communication scheme for NAN should be resilient to outdoors harsh communication environment and instability of wireless links. For these reasons, the simplicity, localized and distributed operation and the low overhead, memory-less and scalability features makes GR a very good candidate for NAN.
Some research papers investigated in the application of geographic routing for AMI networks. Perimeter Stateless Routing (GPSR) [15] was proposed in this context. [16] studies of 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. The authors of [17] 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.

B. Overview of GRACO

GRACO [18] 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 [14]. 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 [18], 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.

VI. Simulations and Results

The performance of GRACO is measured using the WSNET simulator [19].
We generate random topologies with different densities. We evaluate the algorithm according to end-to-end delay, delivery rate and hop count. The simulation results of GRACO are given with 95% confidence intervals. In order to simulate the scalability of the protocol, we run simulations on a network with increasing density. We choose to incrementally add nodes to the network in order to simulate the evolution of the NAN from early stages where just a few customers are enrolled in the network and the nodes are sparse across the selected region to more advanced stages with denser aggregation of nodes representing a more extended version of the NAN.
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	idealmac and 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

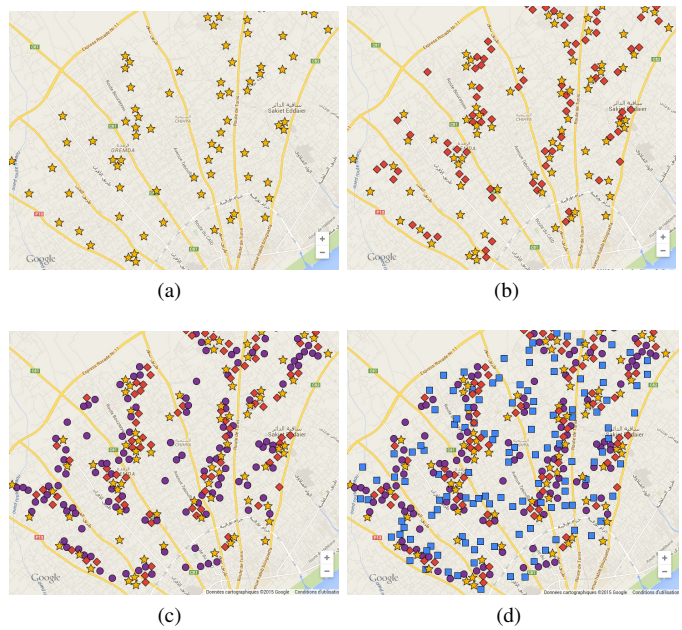


Fig. 3: Stages of NAN extension within an urban region

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. Table I summarizes the simulation parameters. The simulation results show that the more the network is dense the better performs the proposed routing protocol.
The route length is the number of hops a data message needs to go from the source to destination. As the density of the network is increased, shorter paths are found. Specifically, as plotted in figure 4, the average route length drops from 59 hops at network density 10 down to 11.94 hops at network density 40 for an ideal mac layer, and from 37 hops at network density 10 down to 16.32 hops at network density 40 for 802.15.4 mac layer.

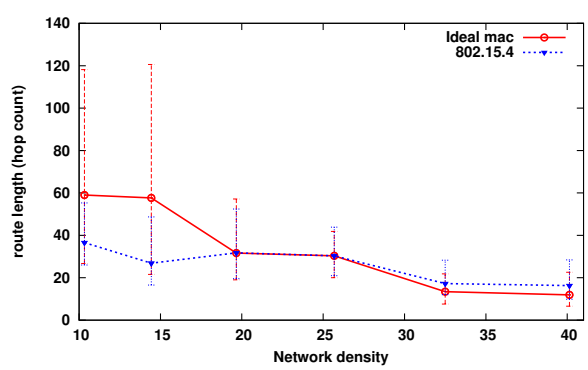


Fig. 4: hop-count

Figure 5 shows the end-to-end delay varying with the network density. The end-to-end delay is the time interval between a given source sends a packet and the destination receives it. For

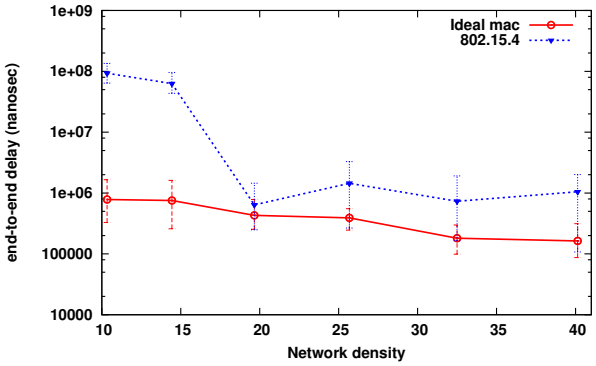


Fig. 5: end-to-end delay

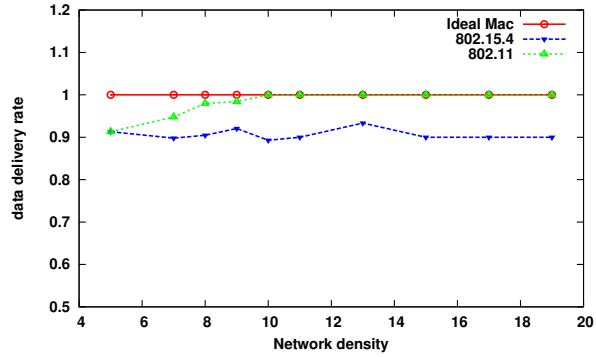


Fig. 7: Data delivery rate on random topologies

an idal mac layer, the average end-to-end delay reduces from 0.781 ms at a network density 10 to 0.163 ms at a network density 40, and for 802.15.4 mac layer, it reduces from 93,183 ms at a network density 10 to 1,049 ms at a network density 40

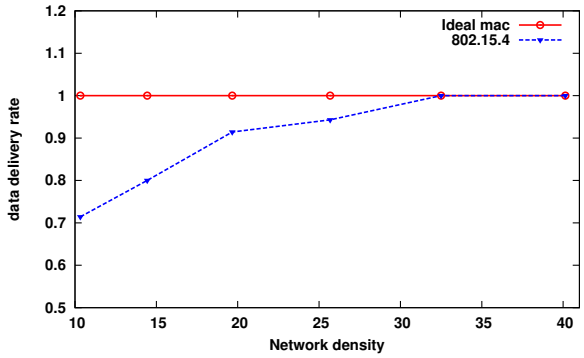


Fig. 6: Data delivery rate

The delivery ratio is the ratio of data packets successfully received by their destinations to all data packets sent by the sources. The data delivery rate is also improved when increasing network density. In fact, figure 6 shows that GRACO provides a 100% delivery rate with an ideal mac, however, for 802.15.4 mac, a high reliability of packet transmission is achieved only in a high density network.
We also run simulations on random topologies in a region of 300×300m region with 250 to 900 nodes and $R = 25$m with random voids. We used different mac layers : ideal mac layer, IEEE 802.15.4 and IEEE 802.11. The simulations results, presented in figure 7, show that GRACO provides a high delivery rate in different mac layers $\geq 90\%$.

VII. Conclusion

A wireless sensor network is proposed to facilitate installation and development of NAN. The proposed ACO aided geographic is scalable and ensures P2P communication allowing for versatile control strategies for the NAN such as fully distributed control to overcome the challenges of centralized control. Delivery rate are within the NAN communication requirements. End-to-end delay decreases with increasing network density or NAN size. This is consistent with the need for larger communication traffic within neighborhood for best control strategies decision.

VIII. Acknowledgments

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