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An Automaton-based Approach for μGrid Communications Control

Jeff Frolik, Anthony Lentine, Chris Palombini and Andrew Seier

Abstract—**In this work, we present a strategy to ensure reliable sensor and control communications in an electric power microgrid environment having a large penetration of stochastic renewable resources such as wind and solar. The proposed multi-state automaton-based approach, that assigns communications priorities in relation to a device's power impact on the microgrid, is shown to satisfy communications bandwidth requirements that are several orders of magnitude higher than that of today's Smart Grid.**

Index Terms—**smart grid communications, QoS, microgrid**

I. Introduction

A proposed strategy to effectively implement the Smart Grid is through the use of interconnected microgrids (μgrids) [i, ii]. A μgrid is an isolated, independent, autonomous network of distributed generation, load and storage. Today, the generation sources in μgrids are mostly fossil fuel based, and often are diesel generators. Currently, effective operation of μgrids is viewed to be of central importance for robust, sustainable operations in isolated, small to modest sized networks such as the Hawaiian Islands or forward operating bases where fuel conveys are costly by many measures [iii]. The transition of μgrids to high penetrations of stochastic renewable resources (e.g., solar and wind) along with distributed energy storage will likely require additional techniques in control and operations as compared to that of the traditional macro-grid and therefore necessitate additional communications requirements [iv]. The implementation of μgrid technologies will not only better utilize the limited available natural resources in isolated systems but also may serve as a means to organize the overall macro-grid.

The power grid of today (i.e., the macro-grid) is a very large network, with over 2700 power plants [v] and 160,000 miles of transmission lines [vi] primarily made up of loads but also consisting of sources of firm generation that use large machines. The stability in the macro-grid comes from its size and the inertia of these generation plants. As such, the power grid is resilient to most transient instabilities introduced by the connection or removal of any one load or generation source [vii]. This characteristic has allowed the macro-grid network to operate robustly without communication between its loads and sources. However, there is a large amount of inefficiency in the current system. Additionally, it is recognized that the present macro-grid is not well adept to handle non-consistent sources of generation (i.e., renewables) [viii].

In contrast, μgrids with high penetration of renewables, will be characterized by stochastic generation and by being electrically small networks. As an example of generation variability, solar photovoltaic farms can reach a new maximum power point on the order of milliseconds [ix, x] due to cloud coverage changes. Similarly, wind power output can be completely lost on the order of minutes [xi]. In a network where renewables represent a large percentage of the power generation, this intermittency can cause instabilities. Conversely, if a relatively large load connects or disconnects without informing the rest of this low inertia network, similar instabilities will be introduced. As such, stability in μgrids is seen to be only achievable through advanced control techniques that require high rates of communications between the μgrid components [xii].

Currently, Power Purchase Agreements (PPA) set ramp rates that require large amounts of local, costly storage and power electronics to regulate overvoltage situations in a μgrid. For example, the Lanai Sustainability Research solar farm has peak production of 1.125 MW but is currently curtailed to 600 kW because it lacks the required storage needed to limit variability to ±360 kW/min, which is 32% of peak a minute. Similarly, Kahuku Wind Power has a peak generating capability of 15 MW, which is accompanied by 10 MWh of storage due to curtailment and its constraint of ±1 MW/min [xiii].

Adapting to stochastic generation (vs. curtailing generation) can be accomplished with the implementation of a broadband communication network in the μgrid allowing sources, loads and storage to share their present and future states, by doing so losses due to stability-based curtailment will be reduced. The necessity for power electronic based inverters and energy storage systems will also be reduced [xiv] allowing for the power grid to operate more efficiently.

However, employing an N-to-N communication scheme, for an N node μgrid, with all nodes having the same communication requirement is not a viable solution as N reaches practical values (e.g., 100s). This is especially true when there is a potential necessity for sub-cycle

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J. Frolik is with the School of Engineering at the University of Vermont, Burlington, VT 05405. e-mail: jfrolik@uvm.edu.

A. Lentine is a Principal Member of the Technical Staff at Sandia National Laboratory, Albuquerque, NM.

C. Palombini and A. Seier are with the School of Engineering at the University of Vermont.

communications (e.g., ~17 ms for a 60 Hz grid).

In this work, we propose proportioning the available communications bandwidth according to a node's power impact (generation, load, or storage) on the μgrid. We also build on previous work that abstracts the μgrid as a collection of autonomous agents and work from the domain of wireless sensor networks that facilitates control of the activity of such autonomous entities. We illustrate that not only can the bandwidth use of a μgrid be controlled through relatively simplistic means but that also entities (sources of generation, load and storage) that have the biggest impact on the μgrid's stability receive, through an uncoordinated manner, the requisite quality of service (QoS).

II. Communications Requirements for μGrid Nodes

A. *μGrid Architecture*

The proposed automaton-based communications control strategy leverages the agent-based abstraction [i] that has been developed for μgrids involving distributed generation ($\mathbf{G}_n$), load ($\mathbf{L}_n$), and storage ($\mathbf{S}_n$) agents as illustrated in Fig. 1. In a single μgrid, any node will communicate information about its current state, forecasted state, and intentions. At the transmission agent level (**T**), a collection of μgrids can be connected to scale the concept beyond that of a single μgrid. These agents regulate power flow from one μgrid to another, sometimes acting as a source and other times acting as a load. Therefore, normal operation consists of a collaboration of μgrids communicating their aggregated states, forecasts, and intentions from the individual agents **G**, **L**, and **S**. In the limit, this model may naturally scale to meet the needs of the Smart-Grid.

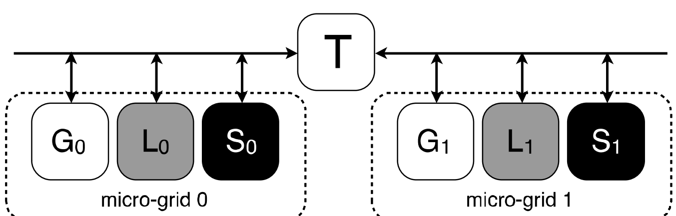

Fig. 1. Agent based model of a μgrid-based power network [i]. Paths indicate information flow.

Physically, this model consists of large range of loads, generators, and storage devices connected via existing power line infrastructure. The communications infrastructure may make use of multiple technologies including wireless, Ethernet, fiber, and power line communication (PLC). It is important to note that these two physical systems, power and communications, are not entirely independent or dependent on one another.

Therefore, although it may be necessary to provide a certain quantitative level of assurance (LOA) [xv] to each agent within the power flow infrastructure, the same does not necessarily hold true within the communication infrastructure. For instance, each house must be assured to have a level of power quality, but an individual house need not have fast, reliable communication with the rest of the μgrid.

Fundamentally, the idea of a Smart Grid and a μgrid may only differ with respect to scope as IEEE has defined the Smart Grid as a "complex system of systems" [xvi]. In this sense, we can construct the Smart Grid using μGrids as the building blocks. However, one major difference remains: autonomous, decentralized control versus organized, centralized control. Though the end goal is a more efficient, reliable, and secure power grid, major differences persist as we summarize in Table I. In short, we find that the data needs for μgrids to be at a significantly higher rate that is foreseen for the present Smart Grid deployment.

TABLE I
Comparing Smart-Grid and μGrid
Sensing and Communications Requirements

Metric	Today's Smart Grid	μGrid
Node Quantity	Millions	Hundreds
Generation	Large inertia centralized power plants	Low inertia distributed renewables & storage
Data Function	Monitoring and protection control (e.g., distribution automation)	Continuous control and monitoring
Node types	Substations, homes and businesses, generation facilities	Generation, load, storage facilities throughout the μgrid
Parameters	Complex phasor measurements in the transmission layer. Electric power (energy) usage as a function of time of day at smart meters	Complex voltage and current throughout the μgrid at all times
Sampling Intervals	Up to 15 minutes	Subcycle to 1/10 sec
Data Volume (per Node)	kbps	Variable (kbps to Mbps)
Stability Source	Grid size, machine inertia	Control over sources, storage and loads.

B. *Communication Requirements*

For the purposes of defining the communications requirements of a μgrid, in this study, we consider μgrids to be geographically small, on the order of a few square miles. Additionally, they are assumed to contain 1-10 sources, 100-1000 loads and 1-5 banks of distributed storage. The μgrid will consist of a range of agents from those few with significant impact on μgrid stability (i.e., stochastic generation sources, large loads, storage sites) to those many with little impact (e.g., individual homes).

If the ~1,000 agents need to communicate on a regular basis to ensure stability in the μgrid with each agent sending 10-bits of information on ten (10) measured metrics, we have the network creating ~100,000 bits per transmission cycle. Using a slow sampling rate of 1 Hz (and no overhead), a bandwidth of 100 kbps would be required for the μgrid communication network. However, going to sub-cycle communications, with packets being sent every 1 ms (i.e., 1000 Hz sampling), increases the network's bandwidth requirement to 100 Mbps. While there are wired and wireless communication technologies that could be employed for µgrids (even at these data rates), this potential communications load motivates an alternative approach.

C. *Load Distribution Model*

The proposed communications control strategy recognizes that the greatest source of instability in the µgrid will be due to the 'largest' agents, i.e., those few agents who either source or use the most power. It is these agents, we contend, that have the greatest need for communications with high quality of service (QoS). As such, we propose to assign access to the communications bandwidth proportionally to agent's power generation/load.

We illustrate this approach by considering a µgrid with total capacity of 1 MW that is to be distributed over 100 nodes (note: these chosen numbers can be readily scaled). We consider three scenarios differentiated by the ratio between the 'largest' and 'smallest' agents in terms of power load/generation. In Scenario A, this ratio is 10; in Scenario B, 100; in C, 1000. Assuming a geometric distribution, Fig. 2 illustrates how the power flow is distributed across the 100 agents in the µgrid considered.

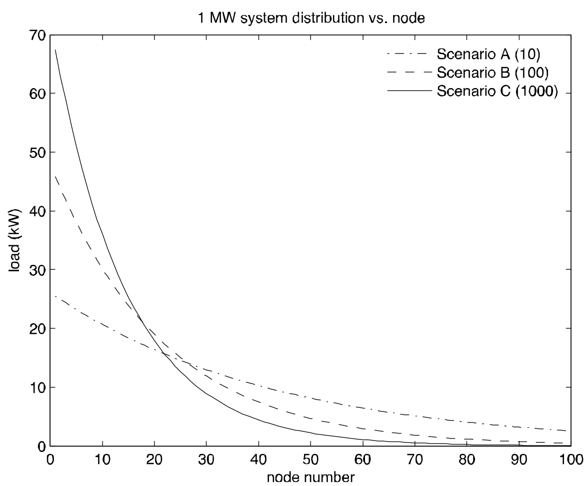

Fig. 2. Geometric model of the distribution of loads (in W) per agent in a 1 MW µgrid. Scenario A has a max/min power load ratio of 10 between nodes; Scenario B has a ratio of 100; Scenario C's ratio is 1000.

Also assumed for this work is that the data sampling rate required for the 'largest' agent is 1000 Hz and for the 'smallest' is 1 Hz. By the geometric distribution of loads illustrated in Fig. 3, we see that the propensity of agents (<10 kW) will require far less bandwidth than required by the 'largest' agents. Or conversely, the majority of the bandwidth will be utilized by only a small percentage of the agents (much as a scale free network). In aggregate, based on our proportioning of the bandwidth, the aggregate data rate is 1.48 Mbps; that is, significantly less than the 100 Mbps required to provide each agent the highest QoS (i.e., access to bandwidth).

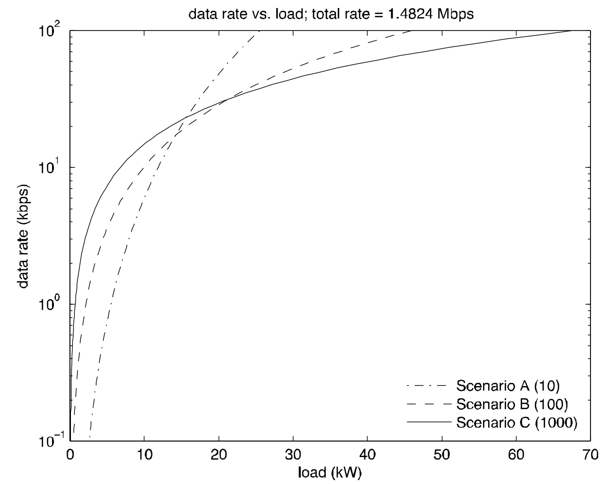

Fig. 3. Proportioning available bandwidth/data rate relative to system power load. Minimum per-node data rate of 100 bps, maximum per-node data rate of 100 kbps.

III. Automaton-Based Design

While allocating the bandwidth to each agent according to Fig. 3 (e.g, via TDMA) is attractive to ensure that the channel is utilized efficiently, we also recognize that the network itself will be dynamic in terms of agent behavior. Not only are individual agent loads stochastic in nature, but also existing nodes may be removed from the µgrid and/or new agents be added. Recognizing that analogous dynamic behavior occurs in wireless sensor networks, we leverage approaches from that domain and propose an automaton-based approach for controlling the communications in a µgrid.

In a distributed wireless sensor network, energy conservation is of paramount concern as sensor *nodes* (comparable to *agents* in a µgrid) are typically energy constrained (e.g., battery powered). Thus, controlling the number of nodes reporting data (one metric for QoS [xvii]) based on the user's need is of interest. For example, a phenomena of interest may only see variation at certain times and thus the end user may reduce the incoming data from nodes outside these windows. An automaton based approach for such QoS control was first proposed using a Gur game strategy [xvii]. This approach implemented a K-state automaton in each sensor node. If a node were in the upper $K/2$ states, it would transmit during a particular *epoch* (comparable to the *minimum transmission interval* in a µgrid). If not, there would be no transmission. The approach was shown to effectively control the number of nodes sending data each epoch up to a maximum of $K/2$. In our problem, this would correspond to limiting the transmissions to only half the agents each epoch.

An alternative, probabilistic K-state automaton was presented [xviii, xix] that illustrated the ability control participation over a wider range than the Gur game approach. A simple version (K = 2) of the probabilistic automaton is shown in Fig. 4. If the node is in the lower state, it will transmit during a particular epoch with probability P_l. If successful and *rewarded* by the end user, the node will move to the higher state and transmit during the next epoch with probability $P_2 > P_1$. Subsequently, if a transmission is not successful or the end user *punishes* the node, the node moves to a lower state. The end user does not track which nodes are transmitting or what is the state of any node. The nodes adjust their state autonomously based only on the global feedback provided by the user (i.e., too much or not enough data is being provided by the network). This automaton design also has shown MAC (media access control) benefits [xx], a concept that we leverage in the work presented herein.

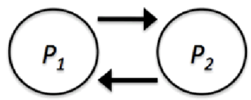

Fig. 4. Simple two-state automaton where P_2 corresponds to a higher probability of transmission and P_1 a lower.

IV. RESULTS

In the wireless sensor network work, each node was assumed to be behaviorally homogeneous and thus the structure of each node's K-state automaton was identical (i.e., each node used the same state probabilities P_1... P_K). The µgrid, in contrast, consists of a collection of heterogeneous agents and we therefore assign their transmission probabilities P_1... P_K proportionally to their power load (e.g., as illustrated in Fig. 3). For our purposes, we consider a simple two-state (i.e., K = 2) automaton where we use the data from Fig. 3 to find the probabilities. Specifically, we set P_2 = *2 x agent's data rate/total data rate* and $P_1 = P_2/4$. With this agent design in place, we now investigate the following two questions. First, with this simple automaton, can the total bandwidth use (i.e., MAC) be controlled? Second, with this control strategy, is the communications bandwidth allocated proportionally to the agent's requirements.

A. MAC Control

In the previous work, the measure for QoS was how many wireless sensor nodes sent data during an epoch. For our µgrid work, we are interested in ensuring that the channel adequately accommodates the submitted traffic. As the agents in the µgrid change in their behavior and number, the automaton design may either over- or under-load the channel with data therefore some system level control is required. To illustrate the controllability of a network of N = 100 µgrid automatons, we compare control of our K = 2 design with a K = 1 design (i.e., an automaton effectively implementing 1-p CSMA MAC).

In Fig. 5, number of data transmissions per discrete time (epoch) is plotted vs. the desired control. The K=2 automaton almost completely satisfies the needs of the control system for this example. As previously demonstrated [xx], this K-state automaton approach results in very efficient bandwidth utilization in comparison to other random access approaches (e.g., 1-p CSMA, ALOHA, etc.). The number of states, K, and their probabilities, P_i, can be refined to improve the systems response and reduce the variability from epoch to epoch [xix]. For the µgrid application space, this control overhead (reward, punishment) is minimal given the ability to readily adapt to the number of agents and their variable loads.

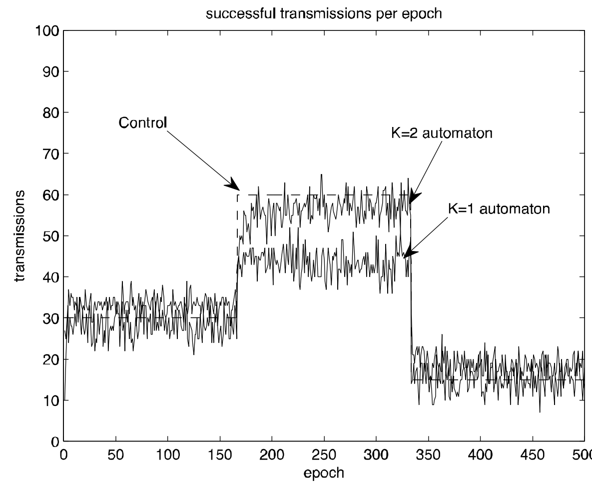

Fig. 5. QoS control of µgrid operating under Scenario C. Control (dashed) and response (solid) vs. epoch for K=1 and K=2 automatons.

B. Agent Transmission Performance

Recall that our objective in this work is to ensure that those agents who have the greatest impact on the µgrid receive access to the communications bandwidth. Our results for Scenario C (where the ratio of power load between the 'largest' and 'smallest' agents is 1000) are illustrated in Fig. 6. We note that indeed all cases of QoS (i.e., available bandwidth) the transmission rate *trend* is proportional to power load (the behavior is not strictly monotonic due to the stochastic nature of the system). We also note, that even the 'smallest' load agents are successful in providing data (albeit less often) to the network. Again, this approach relies only on the probabilistic behavior of the agents in a random access channel. That is, specific portions of bandwidth have not been allocated in advance.

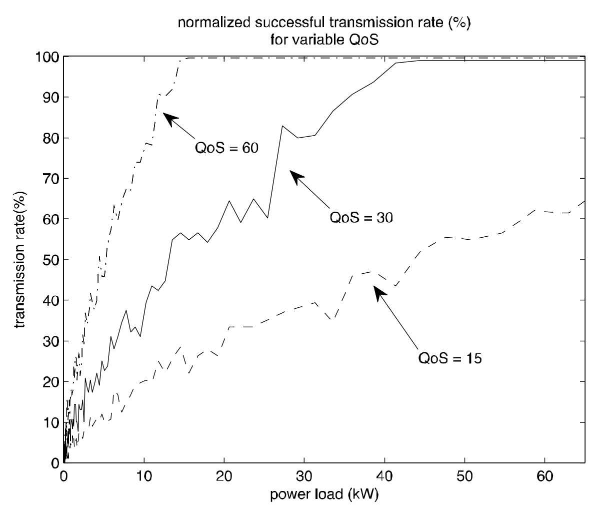

Fig. 6. Node activity rate for µgrid operating under Scenario C. Percentage of successful transmissions normalized by number of epochs. Largest loads are seen to participate at the highest rates. Automaton based design enables virtual priority.

V. Conclusion

In this work, we have adapted previous automaton-based approaches developed for wireless sensor network control to the problem of MAC for μgrid communications. Each μgrid entity employs a multi-state automaton, the state of which dictates the load presented to the channel. Each entity (or agent) is allocated load limits based on their over all impact on the power activity in the μgrid. Results show that not only does the automaton enable the overall network activity to be well controlled with little overhead but also that agents are able to communicate with high channel throughput in a contention based environment.

This work is very much nascent and areas for immediate refinement include determining appropriate power load distribution models for μgrids based on empirical data and conducting more detailed analysis on the *K*-state automaton design and performance for this application space.

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