High Fidelity Cyber Physical Micro-grid Systems

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Abstract—**In order to attain appropriate coordination between utilities and end users while avoiding single points of failure which is typical of centralized controller architectures and dedicated communication links, advanced smart grids should incorporate distributed and autonomous controllers both at the utility side and at the user side in the form of a local micro grid. More distributed and autonomous controllers also reduce the risk for cyber security-related intentional and unintentional outages. However, there is an underlying paradox in the objective of achieving higher reliability through increased use of distributed and autonomous controllers: the more distributed and autonomous the control structure is, the more complex it also tends to be. Since more complex system may be more prone to operational failures, without a proper and careful planning and design, distributed and autonomous control architectures may yield worse reliability performance than expected. The present paper is focused on development of distributed and automated control within a hybrid local micro grid to improve its fault resilience and self- healing.**

***Index Terms*—smart grid, cyber-security, reliability.**

I. INTRODUCTION

Large-scale electrification of air, sea, and land vehicles will transform the way electricity is generated, transmitted, dispatched, and consumed. To cope with these new demands a more flexible, re-organizing, and information-centric cyber physical infrastructure, at least at the distribution level if not throughout the entire system, is necessary. While the extent and final shape of this shift in design and operation of modern power systems is still being contemplated, fundamental expectations from the next generation of power systems have already emerged, and they point to a more customer-friendly perspective. In addition to expecting digital-grade "perfect power" [1], consumers expect the next generation 'smart grid' to keep them informed, empowered, and secured.

Addressing these needs require new design approaches intrinsically build upon enabling technologies including power electronics, signal processing and communication, distributed decision making, distributed generation, and integration of local energy storage in stationary and mobile platforms. Under this circumstance one may introduce reliability as a stochastic optimization process within a cyber-physical system in which schedulable loads, accessible local stored energy and renewable sources can provide system operational flexibility to mitigate problems related to blackouts and brownouts.

These increased requirements suggest that the distribution power grid of the future may benefit from overlaid ac and dc links; Figure 1 illustrates one such possible configuration. The building block of this hybrid distribution, referred to as nano-grid in this paper, is comprised of a multi-port power electronic interface [2] which allows for seamless integration of renewable sources of energy, intelligent management of the energy storage element (stationary or mobile) and scheduling of the local appliances, interface with the ac feeder line and dc linkage with the neighboring nano-grids to form a dc loop among these intelligent elements. An advantageous aspect of this system topology is to enable critical loads to be fed from multiple dc buses with automatic bus selection to ensure uninterrupted operation [3].

In addition to the physical contact which would allow for bidirectional flow of power between ac- grid and other consumers (i.e. nano-grids), existence of a reliable and well secured communication network is essential. A system controller will ensure bidirectional interaction (cyber and physical) between the utility-side network and the customer-side nano-grids. This unit, which may be physically centralized or distributed, oversees the local dispatch of the energy in a way to optimize system reliability, quality, and real time trade of electricity. This central unit is referred to as a micro-grid controller which may also contain its own centralized renewable energy source and energy storage unit [4]-[7].

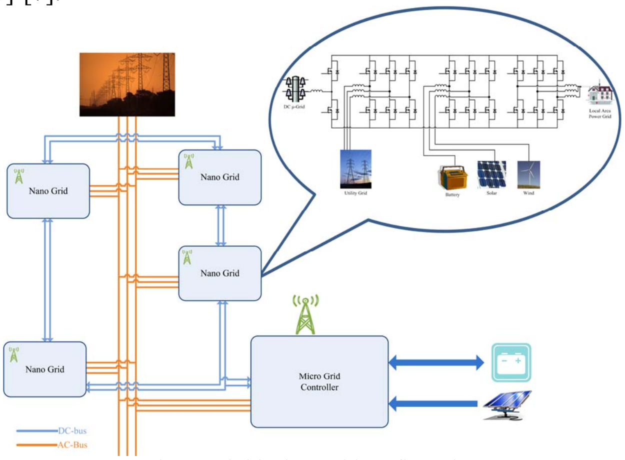


Fig.1. Hybrid micro-grid configuration

This platform introduces flexible joints in the form of extra inter-connects into the currently rigid and inflexible power grid. Introduction of power electronics will not only provide better quality of power to the appliances and electric cars, it also allows for highly efficient operation of major loads such as electric vehicles and HVAC thereby helping to develop a greener environment. Notably, and in addition to peak shaving, this platform can also provide active and reactive power during emergency thereby helping the central utility during stressed periods of time and catastrophes. Finally using the flexibility that is introduced by the nano-grid a more balanced and harmonic free operation in the ac feeder lines can be accommodated. This in turn can result in significant reduction of losses within the distribution system which tends to be current intensive and therefore inefficient. Hence consumers and providers will both benefit from this arrangement.

II. FUNDAMENTALS OF OPERATION

Every member of the micro-grid, namely an MPEI, has information of interest to some subset of cohorts. To enable distributed decision making it is important that information available at each MPEI is communicated to other MPEIs in a reliable and timely manner. In this paper we focus on both aspects of distributed decision making: (a) developing network protocols to enable efficient information sharing, and (b) developing distributed algorithms, that run on the realized network, to make decisions that increase the reliability and availability of the micro-grid[8]-[15].

A.1. Networking the MPEIs

One possible way to enable information dissemination between the MPEIs would be to connect each MPEI to a home network (i.e. local area network). The ISP's infrastructure network could be used to communicate between MPEIs within a micro-grid. However, the micro-grid becomes totally dependent on the ISP(s) for communication. There have been several instances when ISP network outage has coincided with unusual weather conditions. Ironically, it is during these times that the demand for electrical energy could be high and information sharing would be crucial[16]-[19].

Therefore, one can develop a localized wireless networking solution that works with no, or little initial configuration. There are two possible network topologies: (a) a wireless tree-based information gathering and dissemination network, (b) a completely distributed wireless mesh network.

A.2. Airtime Link Metric Limitation

The equivalent of routing, at the MAC layer, for IEEE 802.11s is path selection. Task Group S has specified the Hybrid Wireless Mesh Protocol (HWMP) for path selection. HWMP combines the proactive tree-based protocol with the reactive Ad Hoc on Demand Distance Vector (AODV) routing protocol [24]. For several source-destination pairs tree-based forwarding may be inefficient [20,23,26,28]. There may be a cheaper/shorter direct path between them. AODV discovers such a path on-demand, i.e., only when the source has a frame to send to the destination, but has no direct path to the destination in its path cache. The cost of a path is the sum of the cost of the links comprising the path. The cost of each link, represented by the airtime link metric C_a, is supposed to reflect the expected time to send a fixed size frame across the link. The formula for C_a is:

$$C_a = \left[O + \frac{B_t}{r} \right] \frac{1}{1 - e_f} \qquad (1)$$

Where the constant O represents the channel access time and protocol overheads, B_t is a constant representing a frame of size 1024 bytes, r represents the data rate of the link for the modulation scheme being used, and e_f is the frame error rate for the test frame of size B_t. The airtime link metric could be explained as follows: $(O + B_t / r)$ correspond to the time for one transmission of the test frame. $1/(1 - e_f)$ is the expected number of transmissions needed to successfully deliver the frame across the link. So, the product of the expected number of transmissions for success, and the time for one transmission yields the expected time to successfully deliver the frame across the link. At first glance the airtime link metric appears to make perfect sense. However, it is inadequate because it overlooks the following two aspects of the IEEE 802.11 channel access mechanism:

1. Binary exponential back-off,
2. Carrier sensing based congestion window countdown.

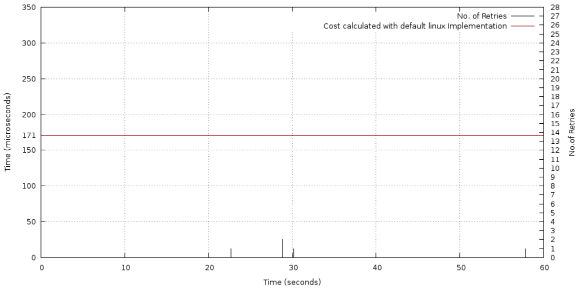
Due to binary exponential backoff the average backoff value doubles with every attempt to retransmit a frame, until the maximum contention window size has been reached. The fact that the term O is a constant implies that in the metric all attempts are assumed to incur the same delay.

Moreover, there is no unique mapping between a chosen backoff value and the time until the next transmission of the frame. Only when the channel has been idle for DIFS (AIFS) amount of time is the countdown resumed for legacy DCF (EDCA, respectively) mode. Hence, if there is a high level of channel activity it may take a long time for a station to count down to zero and transmit the frame.

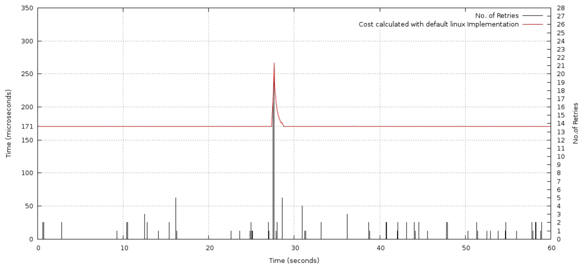
Additionally, there appears to be a significant deficiency in the open80211s implementation of the airtime link metric. If a MAC layer frame is successfully transmitted, e_f for that frame is assumed to be zero. If the frame is dropped because the retry limit is exceeded without receiving a MAC layer ACK the sample is not considered for calculation of the link metric. Thus, the open80211s implementation overlooks the number of attempts needed to successfully transmit a frame.

Figure 2 illustrates the inability of the open80211s implementation to accurately reflect the time to successfully deliver a MAC layer frame across an IEEE 802.11g mode mesh link on channel 13. For the graph in Figure 2(a) the received signal strength was almost always close to -3 dBm (a very good link). The experiment lasted sixty seconds. The x-axis of the figure shows the elapsed time, the y-axis on the left denotes a scale for the airtime link metric (as determined by the open80211s implementation), and the y-axis on the right represents the number of retries needed to send a frame. Most frames are transmitted on the first attempt, with few retries needed for a small number of frames. The airtime link metric is consistently around 171 microseconds. The graph in Figure 2(b) shows the results of the same experiment with the received signal strength hovering around -68 dBm (a decent link, but nowhere close to the one in the previous experiment). While there is a significant increase in the number of frames that needed to be retransmitted, and the number of retries also increased noticeably, the airtime link metric was still unchanged at 171 microseconds, except for a brief period when the link deteriorated significantly and the value increased to about 270 microseconds.

The fact that the airtime link metric computed by the open80211s implementation stays unchanged even when the link quality changes significantly indicates the need for a better metric. In this paper we will develop and implement a new airtime link metric which will do a better job of reflecting mesh link cost. Consequently, wireless mesh path selection for communication between MPEIs will be based on a more accurate understanding of the latency of communication.



(a) Excellent mesh link



(b) Fair mesh link

Fig.2: Retries and open 8021s airtime link metric deficiency.

III. DISTRIBUTED DECISION MAKING

Our goal is to develop solutions that improve the availability and reliability of power supply to electrical devices, while also minimizing the expense to consumer. First, we will assume that each member of the micro-grid operates independently as far as decisions about power consumption are concerned. Then, we will assume that each member of the micro-grid can communicate with each other solely for the purpose of exchanging information about projected energy consumption. This information can be used to possibly reduce consumption and prevent the grid from failing. Finally, we will consider situations wherein members of the micro-grid can also share their stored energy with each other.

As stated earlier, each MPEI can accept power supplied by the utility company, as well as power supplied by a variety of renewable sources. In addition, each MPEI is capable of storing a finite amount of energy that can later be supplied to electrical devices. Each electrical device has a profile which includes its power requirements, as well as whether there is any flexibility in its use. Specifically, a device may belong to one of three usage categories at time t:

1. *Essential and inflexible*: the device has to be in use at time t, for example the lights in the operating room of a hospital or the power supply to the home security system. Energy required for operation of such device d at the time t is denoted by $E_e(t,d)$.

2. *Essential but flexible*: the device has to be used, however its use can be rescheduled but not postponed beyond time a deadline D, for example a dishwasher or clothes dryer. Energy required for operation of such device d at the time t is denoted by $E_f(t,d)$.

3. *Optional*: the use of this device is entirely discretionary. Energy required for operation of such device d at the time t is denoted by $E_o(t,d)$.

The *essential and flexible* devices can themselves be sub-classified as *fixed duty cycle* and *variable duty cycle* devices. An example of a fixed duty cycle device is a dishwasher that has to run once every day. The air-conditioning and cooling system of a building, during summer, is a variable duty cycle device. If the occupants of the building are willing to accept a higher temperature the air-conditioning system can be run at a lower duty cycle. The duty cycle of the device will determine the deadline for scheduling the next operation of the device.

We assume that each MPEI knows the following: the current availability of power from the utility company, the current state of charge of the MPEI's batteries, and the power pricing schedule of the utility [21]. Optionally, each MPEI may also have access to the weather forecast. This can help the software running in conjunction with the MPEI to predict future availability of electrical power from sources like wind and sun. Additionally, we assume that the acceptable duty cycle of each *essential but flexible* device is also known. Based on these information the power consumption of each device, di, at time t can be expressed as a function $f(t, d_i, p, s, w, D)$, where p, s, and w are the pricing information, stored energy in battery, and the weather forecast, respectively.

For an *essential and inflexible device* the power consumption is independent of price, stored energy, etc. Power consumption by such a device is a function of its power consumption history: the longer it has gone without consuming power, and/or the closer it is to the deadline, the greater the probability of consuming power at time t. Power consumption by a member of the micro-grid is the summation of the power consumption of all its constituents, i:e:, $\sum_{\forall i} f(t, d_i, p, s, w, D)$. Note that the MPEI is itself considered as a device that can consume power to charge its batteries.

The total energy cost incurred is less than or equal to the product of the power consumption, duration and price of power that the utility charges. This is due to the fact that some of the power comes from the MPEI's store. However, whether to supply power to a device from the utility or the MPEI's battery is a local decision that is a function of the amount of stored energy and the current price of power. When the MPEI's batteries are close to fully charged, it may be justifiable to supply power from the battery even when the price of power is low. When the battery energy reserve is low, it may be more advisable to draw power from the utility.

The decision whether to use stored energy or draw from the utility, which device(s) to activate and which ones to shut down or duty cycle is a multi-variable optimization problem.

A.5. Optimization Problem

Energy requested by each device $(E(d))$ can be provided using either energy storage or the grid:

$$E(d) = \sum_{t_0 \le t \le M} E_b(t,d) + E_g(t,d)$$

Based on this formulation one can further partition the requested energy based on provider and the type of demand:

$$\begin{aligned} &E_{e,b}(t,d) = \text{essential from batteries} \\ &E_{f,b}(t,d) = \text{flexible from batteries} \\ &E_{o,b}(t,d) = \text{optional from batteries} \end{aligned} \tag{2}$$

By defining similar expressions for the grid contributions one can express the aggregated notations:

$$\begin{aligned} E_b(t,d) &= E_{e,b}(t,d) + E_{f,b}(t,d) + E_{o,b}(t,d) \\ E_g(t,d) &= E_{e,g}(t,d) + E_{f,g}(t,d) + E_{o,g}(t,d) \\ E_e(t,d) &= E_{e,b}(t,d) + E_{e,g}(t,d) \\ E_f(t,d) &= E_{f,b}(t,d) + E_{f,g}(t,d) \\ E_o(t,d) &= E_{o,b}(t,d) + E_{o,g}(t,d) \end{aligned} \tag{3}$$

We plan for the next M hours at the time t_0 .The continuous function representing energy stored in the battery at the time τ is given by $save(\tau, w)$ in which w represent the information set related to weather forecast.

$$\begin{aligned} S(t) &= Energy\ stored\ in\ batteries\ at\ time\ \ t \\ &= \int_{t_0}^{t} save(\tau,w)d\tau + E_s(t_0) - \sum_{\tau=t_0}^{t} E_b(\tau) \end{aligned} \tag{4}$$

$$\begin{aligned} E(d) &= Total\ Energy\ requested\ by\ device\ \ \ d \\ &= \sum_{t_0 \le t \le M} (E_b(t,d) + E_g(t,d)) \end{aligned} \tag{5}$$

$$\begin{aligned} C &= Total\ \ Cost \\ &= \sum_{t_0 \le t \le M} \sum_{\forall d} (E_g(t,d) \times P_t) \end{aligned} \tag{6}$$

The objective of our economical optimization is to minimize cost subject to the following constraints:

$$\begin{aligned} &\sum_{t,d} E_e(t,d) + E_f(t,d) + E_O(t,d) \ge E \ge \sum_{t,d} E_e(t,d) + E_f(t,d) \\ &\sum_{\forall d} E_b(t,d) \le S(t) \quad \forall t, t_0 \le t \le M \end{aligned} \tag{7}$$

While $P_t\ and\ w$ represent the time of use price of electricity and weather forecast to the local nano-grid. It should be noted that while under normal modes of operation economic operation of the system is the target of optimization , during congestion hours and failure of the peak shaving and uninterrupted access to electricity for vital loads are the focus of optimization respectively.

IV. EXCHANGE OF INFORMATION AND ENERGY

MPEI information exchange

In the next stage we will consider the scenario where the MPEIs within a micro-grid will exchange power consumption information with each other. If the overall demand reaches a level that could put the micro-grid in an unstable state, each MPEI may decide to reduce energy consumption by the devices under its control by selectively eliminating or rescheduling consumption. Any solution developed for this situation has to ensure fairness: each participant in the micro-grid should have to make its fair share of cuts to consumption if the demand exceeds supply. Any solution that motivates users to game the system by unduly classifying devices as essential or high priority would not be acceptable. This can be interpreted as an updated optimization problem. Assuming that $E_b^i\ and\ E_g^i$ represent the energy information for the nano-grid "i" the optimization problem can be reformulated to optimizing cost subject to the following boundary conditions

$$\begin{aligned} &\sum_{t,d} E_e(t,d) + E_f(t,d) + E_O(t,d) \ge E \ge \sum_{t,d} E_e(t,d) + E_f(t,d) \\ &\sum_{i} E_{-,g}^{i}(t,d) \le Critical\ energy\ level\ of\ \ grid \\ &\sum_{\forall d} E_b(t,d) \le S(t) \quad \forall t, t_0 \le t \le M \end{aligned} \tag{8}$$

A.7 MPEI energy exchange

Finally, we will consider the situation where an MPEI with abundant energy supply/store can share some of it with an MPEI with a low or depleted energy supply. This will require solutions to match energy-rich MPEIs with energy-poor MPEIs. We believe that this can be formulated as a distributed load-balancing problem. A consumer initiated approach would be one where an energy-poor MPEI initiates communication over the network to identify an energy-rich MPEI from which it could get energy. A supplier initiated approach would be the opposite where an energy-rich MPEI tries to find an energy-poor MPEI. In both approaches, a network wide broadcast to find the right match would be too expensive. So, we propose to perform a sequential search, where MPEIs are interrogated (either randomly, or based on prior information) one at a time to find the right match.

From a networking traffic standpoint selection of the correct approach (consumer initiated, or supplier initiated) is vital. Consider a situation where most of the MPEIs have a very low level of stored energy. If the supplier initiated approach is used, the MPEI with a high level of stored energy will be able to find an MPEI with a low level of stored energy in only a small number of attempts. However, in the consumer initiated approach, a large number of energy-poor MPEIs will be concurrently looking for a small number of energy-rich MPEIs. This will create a high level of contention for the network medium, and increased delay in decision making.

In the full version of this paper a detailed study of both the approaches, and their implementations on our testbed will be provided. Figure 3 illustrates the experimental set up of our hybrid micro-grid which includes four MPEI each with a power rating of 15kW and 20kWH of battery storage system.

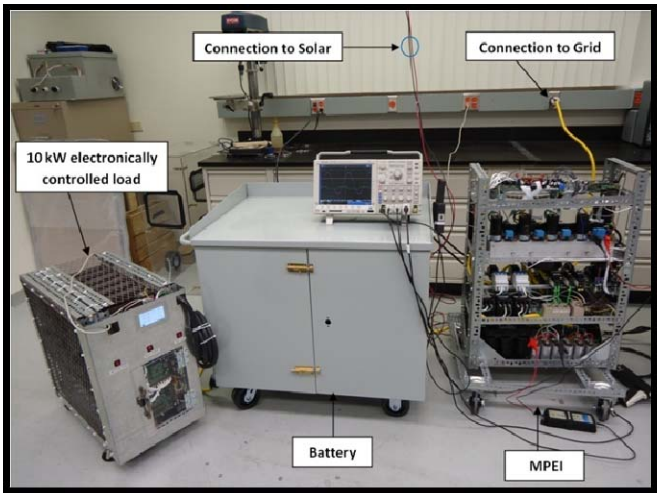


Fig. 3. Experimental setup

V. CONCLUSIONS

This paper explains the issue of reliability in delivering electric power in a hybrid micro-grid in the presence of imperfection of information and energy exchange. The issues related to dependability of wireless communication systems and power electronic based energy processing have been discussed. The final version of the paper will include experimental results to validate the claims.

REFERENCES

1. Sahidehpour M.," Role of smart microgrid in a perfect power system", *IEEE Power and Energy Society General Meeting*, Minneapolis, MN, July 25-29, 2010, pp.1.
2. W. Jiang, B. Fahimi," Multi-port power electronics interface: Concept, modeling, and design", *IEEE Transactions on Power Electronics*, Issue 99, Early access.
3. R. S. Balog and P. T. Krein, "Bus Selection in Multibus DC Microgrids," *IEEE Transactions on Power Electronics*, Early access.
4. P. T. Krein and R. S. Balog, "Cost-Effective Hundred-Year Life for Single-Phase Inverters and Rectifiers in Solar and Led Lighting Applications Based on Minimum Capacitance Requirements and a Ripple Power Port," in *Proceedings, IEEE Applied Power Electronics Conference*, 2009, pp. 620-625.
5. B. Robberts and J. McDowal, "Commercial Successes in Power Storage," *IEEE Power & Energy Magazine, v*ol. 3, pp. 24–30, March/April 2005.
6. P. J. Hall and E. J. Bain, "Energy-storage technologies and electricity generation," *Energy Policy,* vol. 36, pp. 4352-4355, Dec. 2008.
7. Sarah Gondelach, "Current and future developments of batteries for electrical cars- an analysis," Master's Thesis, Utrecht University, Netherland, Nov. 2010.
8. Home Plug Powerline Alliance. http://www.homeplug.org/home/.
9. IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems . Technical report, IEEE.
10. IEEE Guide for Power-Line Carrier Applications. Technical Report IEEE Std. 643-2004.
11. IEEE P2030 Draft Guide for Smart Grid Interoperability of Energy Technology and Information Technology and Operation with the Electric Power System (EPS), and End-Use Applications and Loads . Technical report, IEEE.
12. IEEE Standard for a Smart Transducer Interface for Sensors and Actuators. Technical Report IEEE Std. 1451.1˜4.
13. IEEE Std. for Broadband over Power Line Hardware. Technical Report IEEE Std. P1675.
14. IEEE Std. for Using Wireless Data Communications in Power System Operations. Technical Report IEEE Std.P1777.
15. PUCT - Electric - Rates - Price to Beat Tariffs for Affiliated Retail Electric Providers. http://www.puc.state.tx.us/electric/rates/PTB.cfm.
16. Instrumentation for Increasing Power Flow: Needs, Concepts, Feasibility, and Benefits. Technical Report 1012534, Electric Power Research Institute (EPRI), December 2006.
17. Utility AMI 2008 Home Area Network System Requirements Specification. Technical Report 1.04, Open HAN Task Force, UCA International Users Group, August 2008.
18. Smart Grid System Report. Technical report, U.S. Department of Energy, July 2009.
19. NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0. Technical Report 1108, National Institute of Standards and Technology, 2010.
20. Gahng-Seop Ahn, Se Gi Hong, Emiliano Miluzzo, Andrew T. Campbell, and Francesca Cuomo. Funneling- MAC: a localized, sink-oriented MAC for boosting fidelity in sensor networks. In Proceedings of the 4th international conference on Embedded networked sensor systems.
21. Galen Barbose, Charles Goldman, and Bernie Neenan. A Survey of Utility Experience with Real Time Pricing. Technical report, Ernest Orlando Lawrence Berkeley National Laboratiry, December 2004.
22. Michael Kintner-Meyer, Kevin Schneider, and Robert Pratt. Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids. Technical report, Pacific Northwest National Laboratory, November 2006.
23. B. Lichtensteiger, B. Bjelajac, C. Mueller, and C. Wietfeld. RF Mesh Systems for Smart Metering: System Architecture and Performance. In Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on, pages 379–384. IEEE.
24. C. Perkins, E. Belding-Royer, S. Das, et al. Ad hoc on-demand distance vector (AODV) routing. 2003.
25. Sumit Rangwala, Ramakrishna Gummadi, Ramesh Govindan, and Konstantinos Psounis. Interference-aware fair rate control in wireless sensor networks. In Proceedings of the 2006 conference on Applications, technologies, architectures, and protocols for computer communications - SIGCOMM '06, page 63, Pisa, Italy, 2006.

26. Sumit Rangwala, Apoorva Jindal, Ki-Young Jang, Konstantinos Psounis, and Ramesh Govindan. Understanding congestion control in multi-hop wireless mesh networks. In Proceedings of the 14th ACM international conference on Mobile computing and networking - MobiCom ’08, page 291, San Francisco, California, USA, 2008.
27. Fred Sissine. Energy Independence and Security Act of 2007: A Summary of Major Provisions. Technical Report Order Code RL34294, Congressional Research Service, dec 2007.
28. Wen-Zhan Song, Renjie Huang, Behrooz Shirazi, and Richard LaHusen. TreeMAC: localized TDMA MAC protocol for real time high-data-rate sensor networks, *Pervasive and Mobil computing*, 5(6)750-765, 2009.