Simulation of Minimal Infrastructure Short-Range Radar Networks

Brian C. Donovan[1], David J. McLaughlin
Department of Electrical and Computer Engineering
University of Massachusetts
Amherst, MA 01003
[1]donovan@mirsl.ecs.umass.edu

Michael Zink, Jim Kurose
Department of Computer Science
University of Massachusetts
Amherst, MA 01003

***Abstract*—Distributed networks of short-range radars offer the potential to observe winds and rainfall at high spatial resolution in volumes of the troposphere that are unobserved by today's long-range weather radars. One class of potential distributed radar network designs includes Off-the-Grid (OTG) weather radar networks. These are short-range radar nodes designed to be deployed as part of an ad-hoc network and to limit their reliance on existing infrastructure. Independence of the wired infrastructure (power or communications) would allow OTG networks to be deployed in specific regions where sensing needs are greatest, such as mountain valleys prone to flash-flooding, geographic regions where the infrastructure is susceptible to failure, and underdeveloped regions lacking urban infrastructure. This paper will present a system model and simulation framework for the design of OTG networks. The model estimates the energy requirements of the three major system functions, sensing, communicating and computing, as well as power generated from the solar panel. The simulation will be used to develop an energy cost function to be used in control decisions.**

Fig. 1: OTG Prototype composed of solar panel, battery, data acquisition, wireless communications and marine radar.

I. Introduction

Distributed Collaborative Adaptive Sensing (DCAS) networks have been proposed to overcome the limitations of existing weather radar networks [1]. DCAS addresses some of the limitations of existing NEXRAD class systems by utilizing large numbers of compact X-band radars. These radars are to be distributed on a spacial scale which solves the earth curvature problem. By using smaller radars and making use of network resources, DCAS aims to meet its goal of providing radar coverage below 3 km at a high spatial and temporal resolution. DCAS radars adapt their scan strategies by communicating in a closed-loop fashion with a central systems operation center to dynamically adjust their operation in response to weather conditions.

The DCAS concept may be extended by reducing the system dependence on existing infrastructure, be it the electrical grid for power or wired networking for communications. In this extension, radar nodes would provide their own infrastructure and interface with existing infrastructure at the edges of a DCAS ad-hoc network. A minimal infrastructure DCAS system will be referred to as an "Off-the-Grid" (OTG) radar network [2]. By reducing the infrastructure constraints, OTG networks will allow the DCAS concept to further address additional issues such as: beam blockage in highly variable terrain, temporary deployments, and small basin coverage.

The OTG radar class combines wireless sensor networks [3]–[6] with the DCAS concept. An OTG network may minimize its reliance on existing infrastructure by employing wireless sensor network techniques such as ad-hoc networking, energy harvesting and dynamic management. A detailed description of the OTG concept is available in [2].

Figure 1 is a prototype OTG node [7]. This node combines a solar panel with battery, 802.11b wireless communications and a marine radar to produce a low cost sensing node. This prototype node will be used as part of a small scale system testbed to explore the sensing capabilities of such a radar node. The prototype serves as the basis for developing a model of an OTG node.

Power is consumed within the node by three functions: sensing, computing, and communicating. Maximizing the lifetime of the sensor network, perhaps at the expense of an individual node, will require balancing trade-offs between these three functions. Maximizing the lifetime of the sensor network may be obtained by dynamically adjusting each node's functionality in response to changing environmental conditions.

A system energy consumption model is being developed to investigate trade-offs in the design of an OTG radar network.

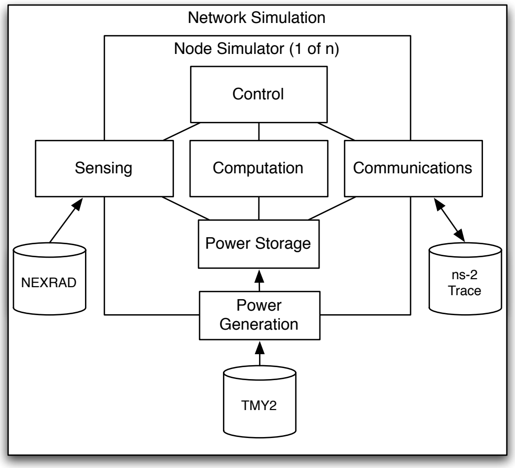

Fig. 2: OTG simulator block diagram.

The trade-offs include the sizing of components, geographical location, node separation, costs and system control. The model will be used to establish the OTG network design space by establishing boundary conditions for each of the systems design parameters. In addition, this model will be used to develop energy related cost functions to be included as part of a dynamic resource allocation algorithm used to control nodes in the network.

Questions to be answered by the model and simulation include: What is the optimal spacing of OTG nodes? What is the impact of varying system parameters such as solar panel size, battery capacity and radar parameters? What is the expected mean time between failures for a network of nodes? And, what is the geographic limit on system deployment?

The model is partially based on the prototype node discussed above but will be general enough to incorporate future technological improvements in node design. The following sections will describe the OTG model and simulation under development.

II. OTG System Simulation

The system is simulated at both the network and node levels as indicated in Figure 2. At the network level the geographic distribution of nodes is studied. This includes network communication between nodes, line of sight for both sensing and communications, and the impact of spatial variance of weather events on the network lifetime.

A. Network Level Simulation

Figure 3 illustrates two potential OTG network deployments. The figure indicates the locations of nodes in the network and the line-of-sight communication links between nodes. These networks are developed by choosing an initial node location and then calculating the location of additional nodes with a given range separation (15 and 25 km in Figure 3). Additional node locations are selected by limiting overlap between nodes and requiring a line-of-sight to at least one existing node. The result is a fully connected network of nodes satisfying line of sight communications.

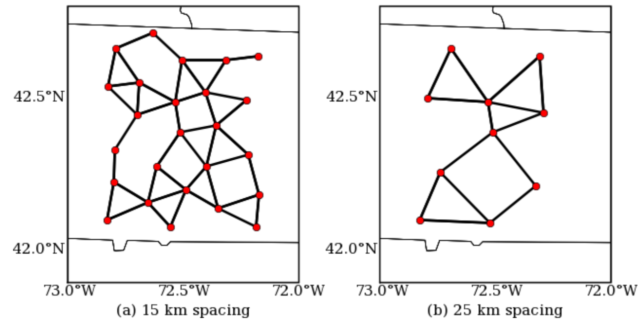

Fig. 3: Example OTG networks for simulation. Dots indicate node location. Black lines indicate line of site communications link. Network is located in Western Massachusetts.

The network of links will be used to simulate the transport of data from nodes in the network to a sink node. Simulation of the network communications will use the ns-2 [8] network simulator to produce trace files of the network behavior. The network simulator includes the behavior of networking route selection protocols and 802.11 networks. The network trace files written by ns-2 will be used by the communications model of the individual node simulator to estimate energy consumption and control communications flow.

At the network level, the simulation is tested using previous weather events from the U.S. National Climate Data Center Storm Events database [9]. Archived NEXRAD WSR-88D data is obtained for severe storm events located in the simulated network location. Data for each of the OTG nodes is extracted from the NEXRAD data determined by the radar range under investigation. The extracted data for each node is then "sampled" to produce a data product for each node. The node performance and energy utilization is examined using a node level simulator.

B. Node Level Simulation

At the node level the performance of solar power generation, the energy costs for sensing, computing and communicating, and the system performance are being evaluated. Additionally the project seeks to develop a quantitative analysis of the impact of different control algorithms on the performance of an OTG network. A discrete event simulator has been written to analyze the state of each node in a OTG network. The four subsystems of each node are simulated at each time-step of the simulator:

1) Solar Power Generation: The solar power generation is modeled using the U.S. National Renewable Energy Laboratory's Typical Meteorological Year 2 (TMY2) data set [10]. This data set provides a 30 year average of hourly solar and meteorological parameters. These parameters are provided for 239 sites across the continental United States and Puerto Rico. Simulation of an OTG network uses the node locations to choose the geographically closest TMY2 site to used for simulation. The global horizontal radiation, diffuse horizontal radiation, and snow coverage parameters are used in the estimation of the expected power generated by a solar panel. The data is transformed to estimate the solar irradiation incident on a tilted panel following [11]. Power generation is estimated based on the incident radiation, the panel size and efficiency, and simulated weather conditions. The power generated is then stored in a fixed capacity battery to be utilized by the remainder of the system.

2) Sensing: A sampled weather field is produced for each node in the network. NEXRAD Level-III data is extracted for each node and then sampled according to the radar parameters for the node. The antenna beamwidths and volume coverage pattern are used to determine field sample resolution and sector size. The radar pulse repetition frequency, system constant and antenna gain are used to filter the original sample field to simulate a minimal detectable signal. These parameters are used to estimate the energy cost to produce the raw time series sample of the weather field and the corresponding time-series output.

3) Computation: Following the sampling of the weather, the model estimates the energy cost of computation. The power required for an algorithm is estimated by measuring the execution time and power consumption on the computer hardware deployed as part of the prototype OTG node. Examples of computation to study include: moment generation, node task generation, network routing algorithms and multi-node data merge.

4) Communications: The communications component estimates the energy required to transport or forward network data using an 802.11b/g wireless network card. Each node is assumed to have bi-directional communications link with its neighbors as indicated by the network layout mentioned above. Data throughput and routing is simulated, using ns-2, based on system parameters such as the distance between nodes, the directional antennas used for communications, and the network card's transmit and receive power levels. The ns-2 trace file is used by the node simulator to calculate the energy requirements for each time-step in the node simulation.

C. Simulation Output

The simulation records a number of parameters for each node including the state of the radar, computer and communications card, the energy being drawn by each component, and the tasks being generated by the control algorithms. These parameters will be used to evaluate the differing control algorithms using a number of metrics including: the total lifetime of network, the life time of individual nodes, the energy required to compute the node control function, and the average time between sensing per unit volume.

III. Example Simulation

Figures 4 - 6 present some of the simulation output for a simple run of the OTG network simulator. In this instance the simulator was used to compare the performance of two single node networks, one located in Amherst, MA (42.392° N, 72.517° W) and Mayagüez, PR (18.203° N, 67.143° W).

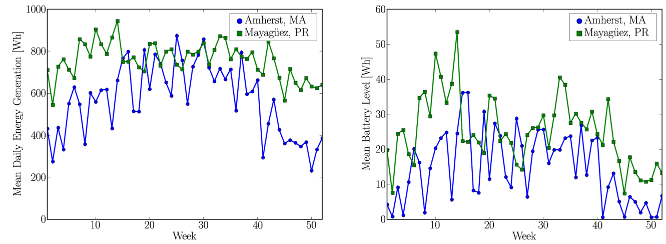

Fig. 4: Energy (a) generation and (b) battery level for 1 m^2, 14% efficiency solar panels with 100% desired duty cycle

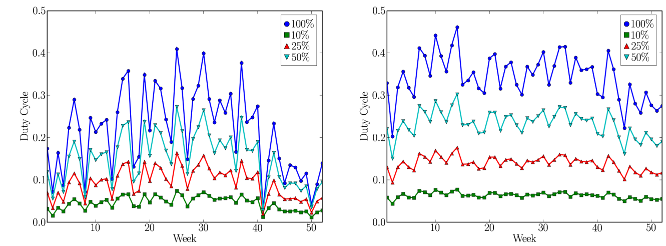

Fig. 5: Node sensing duty cycle Achieved for 4 desired duty cycles: (a) Amherst, (b) Mayagüez

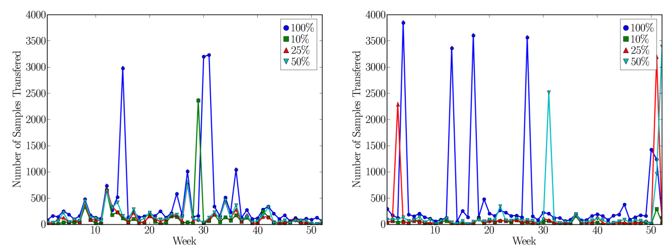

Fig. 6: Number of sample buffers transfered: (a) Amherst, (b) Mayagüez

Both of these sites will host OTG prototype deployments. The simulated nodes in each location are the prototype described above and in [7]. For the purposes of this simulation each component (Sensing, Computing and Communications) was assumed to have two states **on** or **off**. When **off** the component draws no power. When **on** the components draw power at rates estimated from the prototype hardware. These power rates are: sensing 34 W, computation 45 W, and communications 0.41 W. The computer was on if the radar or communications was on, otherwise it was off. The communications was on if the node had data to transmit. Receiving data was not considered.

The desired duty cycle of the radar was varied as was the size of the solar panel used for power generation. At each time step the energy consumption required for sensing with the radar and computer was first estimated. If the battery stored enough energy then the sensing was completed. Next the energy consumption required to transmit any data currently buffered was estimated and completed if the required energy was available. The energy generated by the solar panel was also estimated at each time step. The run simulates the two nodes for one calendar year (starting in January) with a time resolution of 60 seconds. Each of the figures presents cumulative or mean values on a weekly basis.

Figure 4a shows the mean daily energy generation for each node with a 1 m^2 14% efficient solar panel tilted at an angle equal to the node's latitude. The power generated is stored in the battery before being consumed. Figure 4b shows the average battery level for a node with a 100% desired sensing duty cycle. A 100% desired duty cycle attempts to sense at every time step. With a 10% sensing duty cycle the radar sleeps 9 time steps before attempting to transmit.

Periods with an increasing average battery level indicate that for a short period of time there is an excess of power available. Note that the battery level never exceeds 109 W, the required energy level to run both the radar and the computer at the same time. This indicates that the node never generates more power than it would require to run all components at that time. Figure 5 demonstrates this by showing the actual sensing duty cycle for each of four desired duty cycles. The nodes are not able to achieve greater than 50% of the desired duty cycle. Finally, Figure 6 shows the number of samples sent by each node per week. The amount of data transfered is an indication of the nodes utility to an end user.

This simple baseline control of the OTG nodes, a fixed desired duty cycle, indicates the need to develop a more advanced control algorithm to improve system performance. The collecting area of the solar panels may be increased but will impose financial and node size costs. The OTG network control algorithm will build upon the CASA IP1 task generation algorithm [12]. The IP1 algorithm optimizes the sensing of a radar node based on tasks observed by the radar network. The OTG control algorithm will extend the IP algorithm by defining quality functions for the additional system tasks beyond sensing such as data forwarding, data merge and node energy conservation. An energy penalty function will be added to each quality function to include energy as a parameter in the system control. The performance of these algorithms will be examined using the OTG simulator presented here.

IV. Conclusion

We have presented a discrete event simulator for OTG sensor network simulation. This simulation will be used to predict the expected performance of OTG networks and their operational area. A node control function will be developed to improve the performance and utility of an OTG network. This simulator will be used to evaluate potential network control algorithms.

Acknowledgment

This work was primarily supported by the Engineering Research Centers Program of the National Science Foundation under NSF Award Number 0313747. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

References

[1] D. J. McLaughlin, V. Chandrasekar, K. Droegemeier, S. Fraiser, J. Kurose, F. Junyent, B. Philips, S. Cruz-Pol, and J. Colom, "Distributed Collaborative Adaptive Sensing (DCAS) for Improved Detection, Understanding, and Predicting of Atmospheric Hazards," in *Ninth Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface*. San Diego, CA: AMS, 2005.

[2] B. C. Donovan, D. J. McLaughlin, V. Chandrasekar, and J. Kurose, "Principles and Design Considerations for Short-Range Energy Balanced Radar Networks," in *International Geoscience and Remote Sensing Symposium*, Seoul, Korea, 2005.

[3] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," *Communications of the ACM*, vol. 43, no. 5, pp. 51–58, May 2000.

[4] C. Chong and S. Kumar, "Sensor networks: evolution, opportunities, and challenges," *Proceedings of the IEEE*, vol. 91, no. 8, August 2003, DOI: 10.1109/JPROC.2003.814918.

[5] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. Srivastava, "Design considerations for solar energy harvesting wireless embedded systems," in *IEEE International Conference on Information Processing in Sensor Networks*, April 2005.

[6] K. Romer and F. Mattern, "The design space of wireless sensor networks," *IEEE Wireless Communications*, vol. 11, no. 6, pp. 54–61, Dec 2004.

[7] B. Donovan, A. Hopf, J. M. Trabal, B. J. Roberts, D. J. McLaughlin, and J. Kurose., "Off-the-grid radar networks for quantitative precipitation estimation," in *Proceedings European Radar Conference*, Barcelona, Spain, September 2006.

[8] *The Network Simulator*, USC / ISI, http://www.isi.edu/nsnam/ns, Cited: December 7, 2006.

[9] NCDC, *NCDC Storm Events*, http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms, Cited: May 1, 2007.

[10] W. Marion and W. Urban, "User's manual for tmy2s," National Renewable Energy Labratory, http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/, Tech. Rep., 1995, Cited: April 27, 2007.

[11] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, 2nd ed. Wiley, 1991.

[12] D. Pepyne, "Architecture and Algorithims for Collaborative Adaptive Sensing of the Atmosphere," CASA ERC, Tech. Rep., 2006.