Principles and Design Considerations for Short-Range Energy Balanced Radar Networks

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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. Future distributed radar networks will involve thousands of small radars, and the design of these systems will be conducted in a trade-space that balances requirements among radar sensing, communications, networking, and distributed computation functions while addressing infrastructure constraints (such as size, weight, space, and prime power requirements) to achieve cost-effective designs. This paper examines the trade-space and operating concepts behind “Off-The-Grid” (OTG) weather radar networks. These are envisioned as self-contained networks of small remote-sensing / communication / computation nodes, each occupying a volume of 1.5 m³ and capable of operating independent of the wired power / communication infrastructure.

Keywords-component; energy harvesting; DCAS; radar networks;

I. INTRODUCTION

The spectrum of sensor systems may be interpreted using a number of metrics including; size, cost, coverage area, and data bandwidth. If we limit the sensors of interest to terrestrial rain measuring devices, we are primarily interested in in-situ sensors such as rain gauges and radar systems such as the WSR-88D. Rain gauges may provide a lower bound with respect to the metrics of size, individual sensor coverage area, and cost while the WSR-88D provides an upper bound.

While each of these systems may be used to provide rain estimates, it has become clear that these systems alone are unable to provide the coverage required for accurate rain estimates. Rain gages are limited to point measurements, while there are a number of known issues related to WSR-88D class instruments such as the Earth’s curvature and terrain blockage [1].

Researchers have recently begun to develop solutions to the limitations of both ends of the rainfall-sensing spectrum. Medium-range (30 km) X-Band networks have been proposed as a solution to the long-range (> 100 km) radar class issues [2]. At the same time, wireless sensor networks are being developed to extend the coverage area of in-situ based sensing [3,4].

While both of these developments advance sensing technologies, a gap remains between the sensor networks on the in-situ side and the 30-km radar on the other side. This gap exists when a number of metrics are considered including; cost, coverage area and sensing capabilities.

Figure 1 qualitatively compares these four systems with regard to a number of metrics such as those outlined above. The origin of the figure represents the smallest scale for each metric. At present time, the lack of a class of radars suitable for deployment as a wireless remote sensor network defines a gap in today’s sensor technologies.

By scaling the wireless sensor network technologies upward and the 30-km radar technologies downward, a new class of wireless remote sensing networks may be developed. By focusing on networks of 10-km, defining both sensing range and node spacing, radars, and remote sensing technology may be applied to an additional range of applications. This concept paper will focus on one such application, the Off-The-Grid (OTG) radar and its associated wireless radar network.

II. OFF THE GRID RADAR

The OTG radar concept attempts to combine the recent development of energy harvesting techniques in the wireless sensor network community [3,4,5] with the networks of short-range X-band radars [2]. Energy harvesting describes a system’s ability to develop its prime power needs from environmental sources rather than infrastructure sources. Power...
sources for energy harvesting are numerous however, the
power requirements of a radar system suggest use of the high-
est energy density realistic generator, solar photovoltaic panels
[5]. By combining a suitably large solar panel with an energy
storage device (battery) and operating the radar system accord-
ing to a set of energy balanced operating protocols, OTG radars
may provide radar coverage over an extended area while add-
ing a number of new capabilities to traditional radar sensing
applications.

Here we will define an OTG radar as one with the following
characteristics:

- Source its prime power needs using energy harvesting
  rather than existing power infrastructure.
- Transport its data and control communications via a
  wireless ad-hoc communications network rather than
  existing network communication infrastructure.
- Manage its energy consumption by adapting its func-
tionality to the environmental conditions.
- Consume a volume not to exceed 1.5 m³.

As envisioned, an OTG network would be capable of being
deployed with a minimum of support equipment. Independence
of the wired infrastructure allows OTG networks to be de-
ployed 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, certain
high-population areas, and underdeveloped regions lacking
established infrastructure. OTG radar systems may be deployed
in developing countries or remote areas that do not yet have the
power or communication infrastructure to support larger sys-
tems. Networks of OTG radars would be suitable for rapid or
temporary deployment.

OTG radar nodes communicate wirelessly with one-another
by operating as ad-hoc networks, and they distribute computa-
tional functions among various points of computation through-
out the network. The individual nodes derive energy from solar
panels or other self-contained means and therefore OTG net-
works operate under a constraint of limited energy consump-
tion. By limiting the power consumption to that which the radar
is capable of generating environmentally, the maximum range
of the radar and the computational capabilities at the node be-
come constrained.

Power is consumed within the radar node by three functions
of the radar, sensing, computing, and communicating. Maxi-
mizing the lifetime of the sensor network, perhaps at the ex-
 pense of an individual node, will require balance tradeoffs be-
tween these three functions. Appropriate design of energy bal-
ance protocols will require both an a priori knowledge of the
target application and environment as well as dynamic knowl-
edge of the operating environment. Scaling the maximum radar
range to 10-km allows the radar to be located in highly variable
terrain without suffering significant blockage issues. The de-
velopment of a full suite of short (10 km), medium (30 km),
and long (240 km) range radar designs allows the sensing
community to match the radar design range to the target terrain
variability. Reduction in range may also mitigate some system
tradeoffs such as range / velocity ambiguity and node physical
size.

A constrained power radar node will require a novel
method of control that seeks to maximize the lifetime of the
sensor network. Maximizing the lifetime of the sensor network
may be obtained by dynamically adjusting each node’s func-
tionality in response to changing environmental conditions.
This functionality adjustment may be broken in to two forms;
high-level task adjustment (tasking a node to sense versus
compute) or low-level inter-task refinement of operating pa-
rameters such as the radar parameters or CPU clock speed.

III. SOLAR POWERED OPERATION

Assuming the radar parameters in Table 1, a 10 km radar
capable of mapping 20 dBZ reflectivity (light rain) would re-
quire 1 W of average power. The low average transmit power
required for sensing, when combined with a low power com-
puting platform, may be operated using a solar powered system
for sustainable periods of time. Monthly average daily solar
irradiation for Mayagüez Puerto Rico, the site of the OTG test
bed presented in Section V, is shown in Figure 2 [6]. The
minimum average daily solar irradiance, ~ 4000 WH/m², oc-
curs during the month of December. Assuming a commercially
available solar panel such as the Kyocera KC60 with ~ 0.5 m²
of collection area with a 12% efficiency, a minimum of ap-
proximately 240 WH may be generated each day.

![Mayagüez, PR Average Daily Irradiation](image)

Figure 2. Mayagüez Puerto Rico average daily solar irradiance assuming a
southward facing solar panel with 18° tilt.
Assuming this generated power is stored in suitably large battery, a multiple day reserve of generated power may be stored. In order to balance energy consumption with generation, average consumed power for each node, assuming 24 hrs operations, should not exceed 10W. Assuming 30% efficiency of the transmitter and an equal power consumption for the receiver yields 6W average power consumption by the sensing system of the radar, leaving 4W average for computation and communications. With today’s low power CPUs consuming tens of watts of power, power management of all three systems will be required to meet the 10W average power requirement for sustained operation. This power management requirement may be accomplished by dynamically adjusting individual node tasks in response to environmental conditions.

IV. NETWORK TASK ALLOCATION

Power management of an OTG node may be accomplished by gating, alternating between an on and off state, of an individual node’s subsystems. This gating may be done using the network’s knowledge of current environmental conditions. Gating may be accomplished by a number of methods determined by the technology used. Examples include: putting individual components such as the sensing RF or the control computer to sleep, adjusting estimate precision by lengthening or shortening dwell times, and improving minimum sensitivity by increasing the pulse length of a pulse compression wave form. A number of operating modes may be defined which are selected dependent on the operating environment. The operating parameters are set according to a set of basic principles.

- Under clear air conditions the primary network and node objective is to generate and store power. Surveillance should be limited to augmentation of existing radar coverage.
- Stored power should be consumed in proportion to the utility of the data to be acquired.
- Complete network knowledge of the storm should be used in optimizing power consumption.
- When possible computation tasks shall be completed remotely from a storm to make use of clear air conditions.
- Sensing performance shall be dynamically adjusted based upon utility of the data.

For the sake of simplicity four operational modes will be considered;

**General Surveillance:** Obeying the first principle and operating in the non-precipitating environment, the individual node’s objective is to harvest a greater amount of energy than is consumed through operations. Once maximum energy storage has been reached, all energy harvested may be utilized immediately or will be lost. Volume coverage pattern (VCP) in this mode would be designed to complement existing WSR-88D coverage on an individual node basis. Volume updates would occur at sparse intervals, for example every 10 minutes, to maximize energy harvesting.

**Rain Prediction:** Obeying the first and second principles, and operating in an imminent-storm environment. Node objective is to balance energy harvesting with consumption. Volume update times would be increased, ~ 5 minutes. Sensitivity would be increased to sense low dBZ reflectivity, ~ 20 dBZ. Dwell times would not be increased therefore limiting the precision of the estimates, ~ 3 dB.

**Rain Mapping:** Obeying the second principle and operating in the precipitating environment. Nodes in this mode would focus on high resolution, low standard of deviation rainfall estimates. Nodes would be allowed to consume energy from battery storage. Volume coverage would focus on base reflectivity allowing dwell times to be increased to improve estimate precision, ~ 1 dB.

**Computation:** Obeying the third and fourth principles, network computation such as multi-sensor data fusion, response to user queries or network optimization would be pushed to nodes operating in clear air environments. It is assumed that operating in the clear air environment will allow the nodes to continue to generate energy from solar input.

Adjusting node performance and task may allow system lifetime to be extended to 24 hr operation for weeks at a time using only solar based input. An implicit assumption is that the value of data is not a constant function of time. For example, during a developing storm, high sensitivity lower precision data may be of greater value than low sensitivity, high precision data. Likewise during periods of high rainfall intensities, where the minimum expected reflectivity is higher, ~ 40 dBZ, sensitivity may be sacrificed.

Figure 3 illustrates an example time evolution of an OTG network covering the island of Puerto Rico. In panel A, a new storm cell is detected while the majority of the network nodes are in the General Surveillance mode. This detection may have been from the local NEXRAD or from local OTG nodes in the general surveillance mode. Following detection, nodes in the predicted path of the storm cell enter the Rain Prediction mode looking for low rain rate precipitation and storm precursors. As the storm cell moves across individual nodes they are placed into Rain Mapping modes, additional nodes are placed into computation mode to accomplish network processing (B). As the storm area or complexity increases the network adapts by tasking more nodes for Rain Mapping or Computation (C,D).

![Figure 3. OTG Wireless Radar Network Operational Concept](image-url)
Distributing computation away from the nodes that are acquiring data may allow the network to improve data utility by intelligently deploying energy within the network. By taking advantage of the special variation within the storm environment, network computation may be completed by nodes not needed for sensing of the storm. By distributing computation, and hence power loading throughout the network, total average network power consumption may be lowered.

Distributing computation may imply an increased amount of network traffic moving data between nodes for computation. Potential power tradeoffs between sensing, computation, and communication will need to be examined in depth. In addition the utility of various quality rainfall data will need to be defined in order to numerically characterize the sensing modes outlined above. These as well as other theoretical studies of the OTG concept are currently under way.

V. OFF-THE-GRID TESTBED

An OTG testbed focusing on Quantitative Precipitation Estimation is being constructed in western Puerto Rico. Four OTG nodes will be deployed in order to demonstrate the concepts outlined above. The expected coverage area of the network is illustrated in Figure 4.

The network will be based at the University of Puerto Rico Mayagüez and will utilize commodity 802.11 WiFi networking with high gain antennas to forward data to the University for storage and additional processing. Network links will be upgraded to the higher performance 802.16 WiMAX standard when available. The prototype OTG nodes are being designed using commodity components. Each node will be a dual-polarized solid-state based radar. Each node will operate at X-band with a ~ 4° beamwidth antenna for sensing. X-band operation is motivated by the desire to limit node volume to 1.5 m³. X-band operation combined with the ~ 4° beam will allow for ~ 720 m cross-range resolution at 10 km using a ~ 0.33 m diameter antenna. X-band operation will introduce attenuation into consideration for sensing operations, the limited range of the nodes should limit the impact of attenuation. While not examined initially, higher frequency operation may be explored at a later date.

Computation for the nodes will be provided using low power x86 compatible embedded computing systems. Initial nodes will utilize processors running ~ 600 MHz. Identifying the required computational needs will be a prime goal of the initial testbed.

The nodes will be powered using a Kyocera KC60 described above combined with a 84 Ah deep cycle battery. Peak power load is expected to be ~ 100 W with all subsystems active.

The prototype nodes will serve to demonstrate the concepts laid out in this paper. The node hardware will not be optimized for power at this time; power optimization will be limited to software operation. Following successful proof of concept, optimization of the hardware (with respect to power consumption) will be warranted.

VI. CONCLUSIONS

We have presented a concept of using 10 km radars powered with solar and battery systems in combination with energy balanced protocols to enable rapidly deployable self sustainable remote sensing of large volumes of the boundary layer. Such a system will enable the deployment of radar coverage in areas currently unobserved such as mountainous terrain or remote areas. This work in progress is being examined both from a theoretical and experimental viewpoint in order to examine the numerous issues to be resolved for optimal implementation of such a system. The power requirements for in network communications and computation must be characterized in order to begin developing the energy balanced protocols. The prototype OTG nodes being developed for the Puerto Rico testbed will provide the basis for a complete understanding of the power requirements for producing quantitative precipitation estimates using radar.