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Off-the-grid radar networks for quantitative precipitation estimation

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1 Introduction

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. Dense networks of short-range radars may be used to defeat the Earth curvature problem that prevents current operational radar networks from observing the boundary layer (McLaughlin et al., 2004). Off-the-Grid (OTG) weather radar networks are envisioned as a class of distributed radar networks comprised of small, self-contained "nodes" each capable of performing radar-sensing, node-to-node communication, and data processing/ computation functions. In the OTG concept, each node should be capable of operating completely independently of the existing prime-power and communication infrastructure. This independence on existing infrastructure makes OTG networks unsusceptible to infrastructure power and communications failure. Moreover, this enables OTG networks to be set up and deployed in a wide variety of locations, including, mountain valleys prone to flash-flooding, underdeveloped regions lacking built-up infrastructure, geographic regions where the infrastructure is particularly susceptible to failure, and high-population areas where it is costly or logistically prohibitive to adapt the existing infrastructure to support a dense radar network.

OTG radar nodes communicate wirelessly with one-another by operating as an ad-hoc network, and they distribute computational functions among various nodes throughout the network rather than relying on a single large computing facility. The individual nodes derive energy from solar panels, or other self-contained means, and therefore OTG networks operate under a constraint of *limited energy consumption*. For an OTG network to operate over extended periods of time during severe and changing weather energy generation and consumption must be balanced. These systems will balance the allocation of energy to the different node subsystems through dynamic control decisions. For example the maximum lifetime of a network (between solar charges to the panels, for example) may be achieved by concentrating sensing functions on specific nodes in geographic proximity to the storm, and paying the energy cost to communicate the data such that data and computation functions are conducted at nodes geographically distant from the storm. Sensing, communicating, and computing tasks would then be redistributed throughout the network as the storm cells migrate over the coverage area (as illustrated in Figure 1), in such as way that it maximizes the ratio of useful information collected to power consumed.

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2 Operational Concept

Off-the-Grid (OTG) radars combine short-range radar technology with wireless sensor network technologies. Current-generation wireless sensor networks are composed of self-contained nodes having low energy-consumption

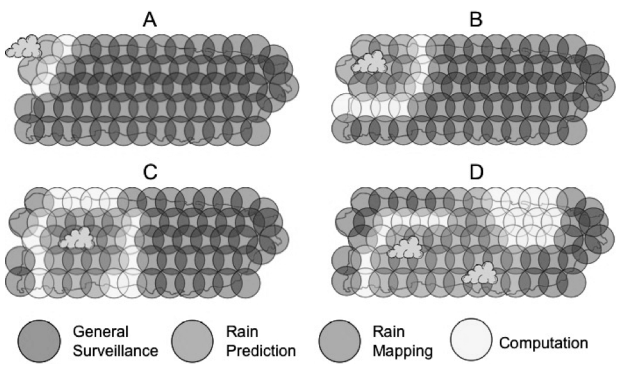

Fig. 1. OTG operational concept; dynamically adjust node function as a spatiotemporal function of precipitation.

sensing functions, deployed in networks to cover large areas (Pottie, 2000; Chon, 2003). Wireless sensor nodes are now being designed to obtain energy from the environment in order to prolong their operation (Raghunathan, 2005).

By combining the wireless sensor network technologies and the short range radar technologies, a new class of wireless remote sensing networks may be developed. A distinct challenge in these systems is the substantial energy requirement of the sensing function, since radars are notoriously “power hungry” devices. Since the energy required of a radar varies as the square of the operating range, restricting the latter to ~ 10 km results in modest energy requirements for the sensing function in these networks. Using a reasonably-sized solar panel (with a battery) and operating the radar system according to a set of energy balanced protocols, OTG radars can thus provide radar coverage over an extended region, while comprehensively mapping low-altitude regions, without reliance on the built infrastructure.

An OTG radar node has the following characteristics:

- Prime power needs are sourced using energy harvesting rather than existing power infrastructure.
- Data and control communications are transported via a wireless ad-hoc communications network rather than existing network communication infrastructure.
- Energy consumption is managed by adapting node functionality to the environmental conditions.

OTG radar nodes communicate wirelessly with one another by operating as ad-hoc networks, and they distribute computational functions among various points of computation throughout the network. The individual nodes derive energy from solar panels or other self-contained means and therefore OTG networks operate under a constraint of limited energy consumption. 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 become constrained.

Power is consumed within the radar node by three functions of the radar; 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. Appropriate design of energy balance protocols will require both an a priori knowledge of the target application and environment as well as dynamic knowledge of the operating environment.

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 functionality 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 parameters such as the radar parameters or CPU clock speed.

Power management of an OTG node may be accomplished by adjusting the operating parameters of various subsystems. Power management techniques such as voltage scaling are well known in the microprocessor community (Intel, 2004). The networking subsystem may adjust transmission power strengths and data rates. The sensing subsystem may adjust the volume coverage pattern and transmitted waveform. The node may adjust the overall duty cycle of individual components in order to maximize data utility and system lifetime.

By operating as a geographically distributed network, individual nodes may adjust their parameters based on the spatial nature of weather events (Fig. 1). As a storm event crosses through the network domain, nodes within sensing range sample the storm and communicate to nodes away from the event thereby dispersing the energy costs throughout the network and increasing overall lifetime.

A detailed presentation of the OTG concept may be found in (Donovan, 2005).

3 Prototype OTG Node

3.1 Hardware

The principle goal of the initial OTG network is to serve as a proof of the operational concept. Each of the three main components of the node; sensing, computing; and communications are implemented using commodity hardware. The sensing function of the OTG prototype (Fig. 2) is provided by a RayMarine Radome 24” marine radar (RayMarine, 2006). The node computer is a VIA MII-6000 low power embedded computer running Linux 2.6. Communication is provided using a Proxim 802.11 b/g wireless card and high gain directional antennas. The radar is integrated to the computation system using an Adlink analog to digital converter, a Microchip USB PIC demo board and a custom interface board.

Fig. 2. OTG prototype undergoing testing.

Power is provided to the system using a 12V photovoltaic system. A Kyocera 60W solar panel generates energy which is stored in a 110 Ah battery. A maximum point tracker (MPT) is used to charge the battery as well as provide power to the rest of the system (Fig. 3).

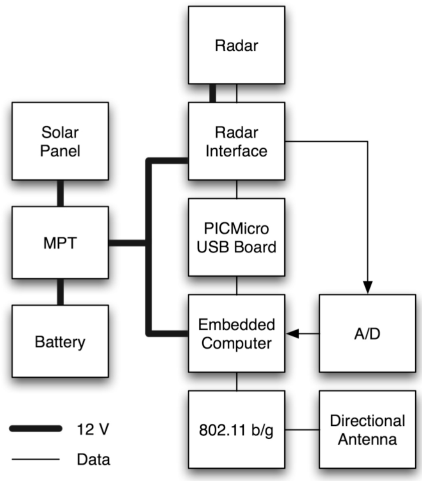

Fig. 3. OTG prototype block diagram

3.2 Sensing Capabilities

The RayMarine radar used to provide the sensing functions of the OTG prototype was designed for marine collision avoidance (Table 1). While the radar is sufficient for providing a proof of concept for the OTG concept it will need to be upgraded to have sufficient capabilities for precipitation sensing.

Table 1. RayMarine 24" 4kW specifications

Antenna Type	patch antenna
Dimensions	599mm x 277 mm
Center Frequency	9.41 GHz
Peak Power	4 kW
Pulse Length	1μs
PRF	740 Hz
Horizontal Beamwidth	3.9°
Vertical Beamwidth	25°
Maximum Range	48 nm[1]
Power Consumption	10W standby, 34W transmit

The radar provides reflectivity only and has a broad fan beam antenna pattern which is not ideal for a precipitation radar. However the radar will be sufficient to demonstrate the OTG concept and may be upgraded with a narrower antenna at a later date. This radar is expected to have a sensitivity of 35 dBZ_e at 10km subject to 15 dB two-way attenuation. An antenna upgrade is being considered 4° x 4° pencil beam antenna, being developed at the University of Puerto Rico Mayagüez, which will improve the sensitivity to 28 dBZ_e (Trabal, 2006). The upgrade antenna will improve both antenna gain as well as reduce ground clutter by eliminating negative elevation angles.

3.3 Power Consumption

Power is consumed in the radar by the electronics required to control the radar, the motor rotating the antenna and the magnetron (and supporting hardware) producing the pulses. In the standby mode the electronics and magnetron heater are active but the antenna is not rotating. When the radar is transmitting the antenna is rotating and the magnetron is active. The breakdown of sensing power consumption is presented in Table 2.

Table 2. RayMarine power breakdown

Heater & Controller	10W
Motor /Inefficiencies	21W
Average Radiated Power	3W
Total (Transmit)	34W

In addition to the sensing function, power will be consumed by the computation and communication functions of the OTG node. The computation function may be broken into three main components; the motherboard (VIA Technologies, 2004), the PCI A/D card (Adlink Technologies, 2005), and a compact flash card for storage. The worst-case power consumption for the three components is presented in Table 3. The power consumption is comparable to that of the sensing function. If the sensing function is not being operated the A/D would not be required therefore reducing the power consumption of the computation system by 40%

Table 3. Computation power breakdown

Motherboard	17W
A/D	13W
Storage	3W
Total	33W

The final main function of an OTG node is the communications function. The OTG prototype will use 802.11g for point-to-point wireless communications. A PCMCIA wireless card will be paired with a passive directional antenna in order to achieve long distance communications (~ 10 km). The wireless card currently being used (Proxim Wireless, 2006) draws approximately 2W when transmitting and 1.4W when receiving. Table 4 presents the worst case power consumption of each of the three functions of the node.

[1] When operated as a marine radar.

Table 4. OTG prototype power breakdown

Sensing	34W
Computation	33W
Communications	2W
Total	69W

4 Solar Powered Operation

The OTG network will be deployed in western Puerto Rico. Given the panel selected for the prototype node and the average daily solar irradiation for Mayagüez, Puerto Rico a minimum of approximately 240 Wh may be generated each day (Garcia, 2004). Assuming this generated power is stored in a 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. Given the expected energy available daily from the solar panel the OTG prototype node would have an expected lifetime of 3.5 hrs per day if operated continuously. Operation for a full 24 hrs will require reducing the operational duty cycle below 15%.

An initial power management scheme for the OTG will rely on switching the power state of the node. Four power states may be defined based on the power breakdown given above. In the first power state, S0, only the network card is operating and the computer is sleeping in a "Wake-on-LAN" mode. The sensing function is off and is not drawing power, but the node is able to communicate with other nodes in the network. The second state, S1, adds the computation function but does not enable the A/D or sensing functions; in this state, the node is able to support data processing functions. The third state, S2, places the RayMarine radar into its *Standby* state, which will warmup the magnetron but not rotate the antenna. The fourth and final state, S3, enables both the radar and the A/D. These four states are compared in Table 5.

Table 5. OTG power states

Function	S0	S1	S2	S3
Network	•	•	•	•
Motherboard		•	•	•
A/D				•
Radar (Standby)			•	
Radar (Transmit)				•
Power Consumption	< 5 W	22 W	32 W	69 W

5 Deployment

At the time of this writing (June 2006) the prototype node is undergoing testing at the University of Massachusetts (Fig. 3). Following the testing of the initial node three additional nodes will be constructed and field-tested at the University of Massachusetts before being deployed in western Puerto Rico as part of the CASA student test bed.

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