Model-Driven Dynamic Control of Wireless Sensor Networks

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Overview

- Wireless sensor nets
  - evolution toward diverse, application-dependent deployment densities and node capabilities
  - a new technology for measuring environments
  - motivating application: **revolutionize understanding of environmental change**
- Project aim
  - forecast how altered climate and CO_2 will impact biodiversity and carbon storage in the biosphere
- Approach: dynamic sensor networks
  - Deeply embedded distributed intelligence for model inference and prediction

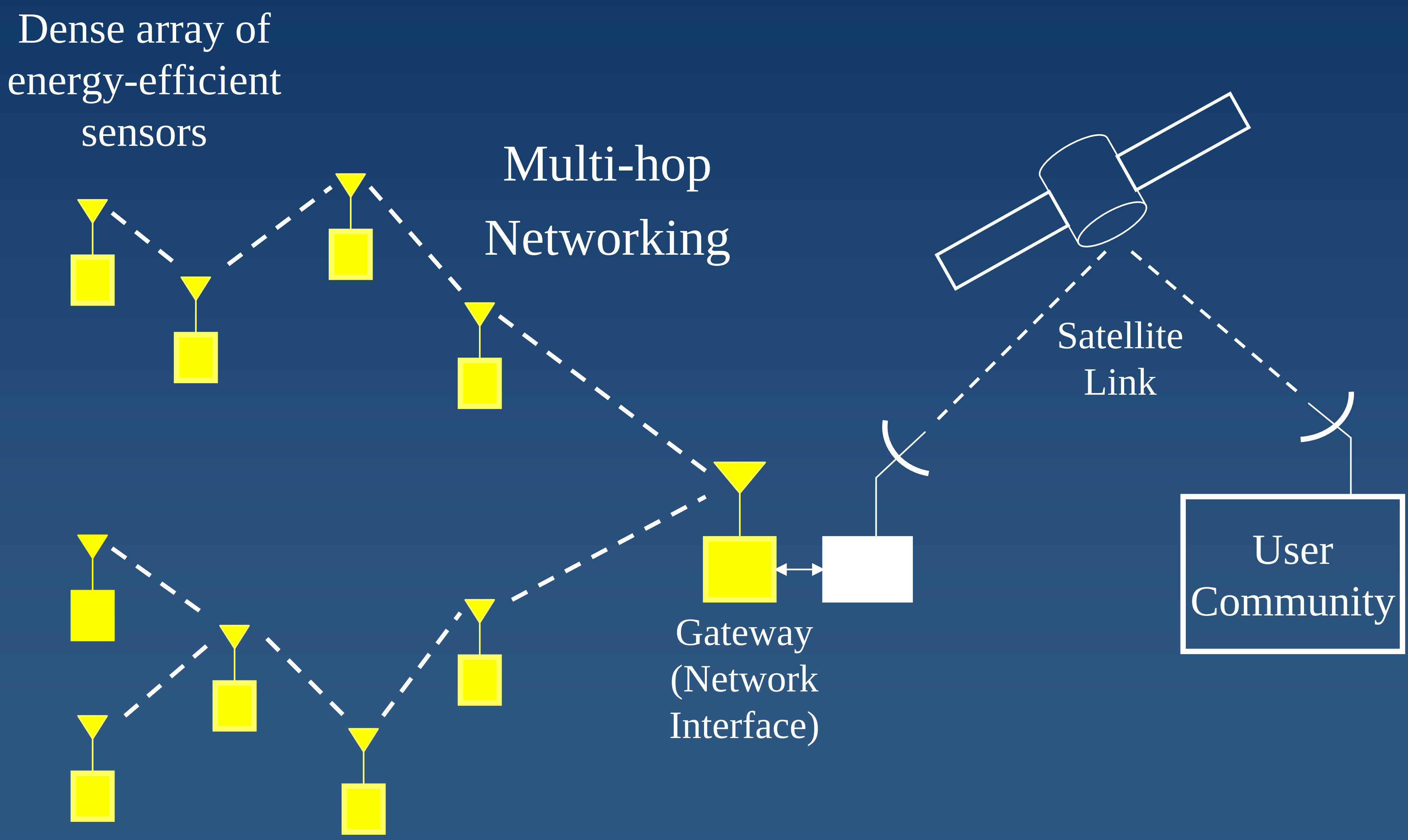
Outline

- Sensor net design and implementation
  - Node and software design
- Dynamic sensor networks
- Algorithms and software
  - Data service layer
  - Model-driven control
  - Research challenges
- Concluding remarks

Requirements – Environmental Sensing

- Minimal invasiveness
- Long battery life
  - Aggressive energy management
  - Target: > 12 months
- Scientific accuracy
- Support of a broad spectrum of probes
- Support transparent incremental deployment
- Scalable in network size and density
- Ease of installation and maintenance
- Support of internet connectivity via
  - Terrestrial (cellular)
  - Satellite
- Rugged, weatherproof packaging
- Low life cycle cost

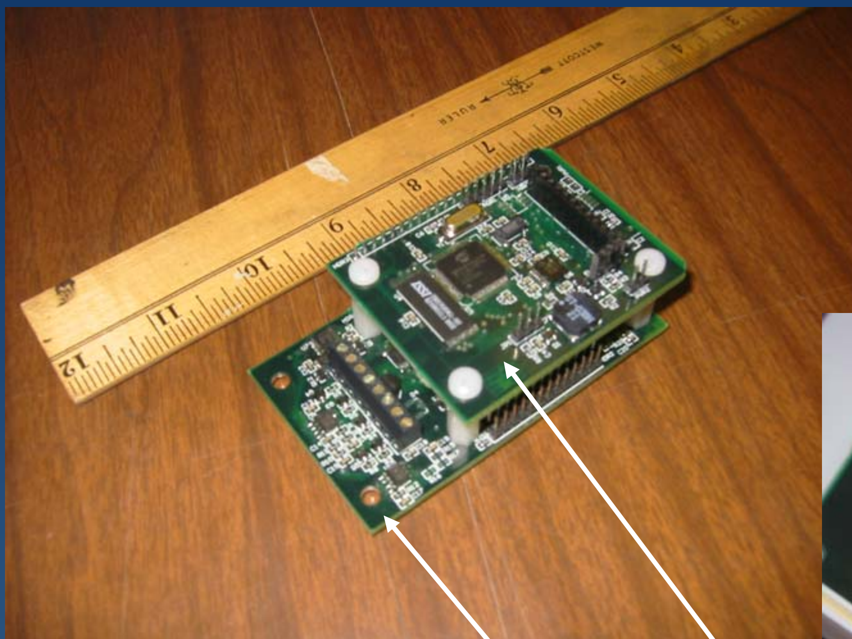
Concept


Dense array of
energy-efficient
sensors
Multi-hop
Networking
Satellite
Link
Gateway
(Network
Interface)
User
Community

2nd Generation WiSARD

Modular hardware design

- Dual-processor architecture
- Three-board stack



Gateway nodes will use memory/time board in place of sensor data acquisition board

G2 WiSARDNet Design

Communication and Networking

- 902 – 928 MHz ISM band
- Non-Coherent Binary FSK (NC-BFSK) modulation
- Slow time/frequency hopping spread spectrum via pseudo-random number generator
- CRMA radio channel sharing algorithm
  - Distributed control
  - Local information
  - Scalable

Self Organization

- Periodic search for new nodes
- On-demand search for lost nodes (under development)
- Can add, move, or delete nodes

Power Management

- Monitor power status
- Report battery voltage
- Adjustable radio transmit power (under development)

Scheduler

- Dynamic scheduling of communication
- Online-configurable sample rate (under development)

User Interface

- Command line from PC
- User selection of ID, sample rates
- On-line diagnostics

G2 WiSARD Capabilities

Built-in probe interfaces

- 12-bit A/D conversion
- 4 temperature channels
  - thermocouple
- 4 light (PAR) channels
  - photodiode
- 2 general purpose probe channels, two power outputs and two CCP modules (Capture/Compare/PWM)
  - Soil moisture
    - Decagon Ech2oprobe
  - Serial communication with intelligent probes
  - Sap flow (future)

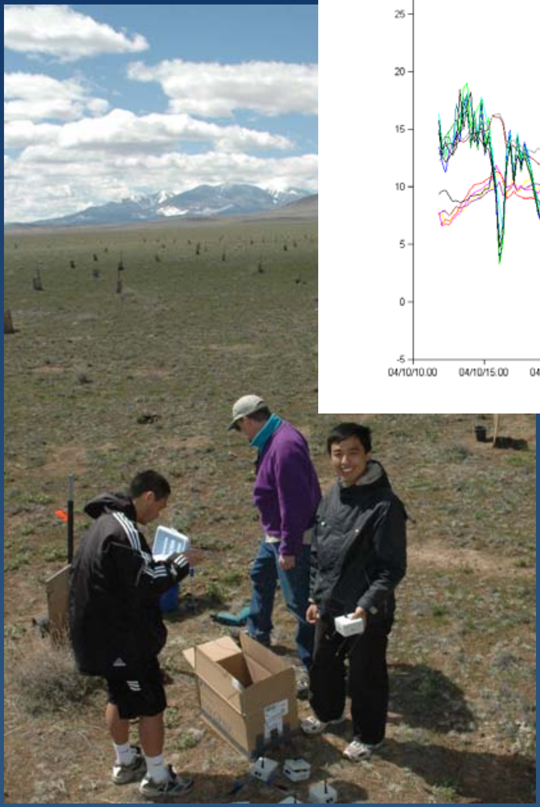
Interface for multiple additional intelligent probes

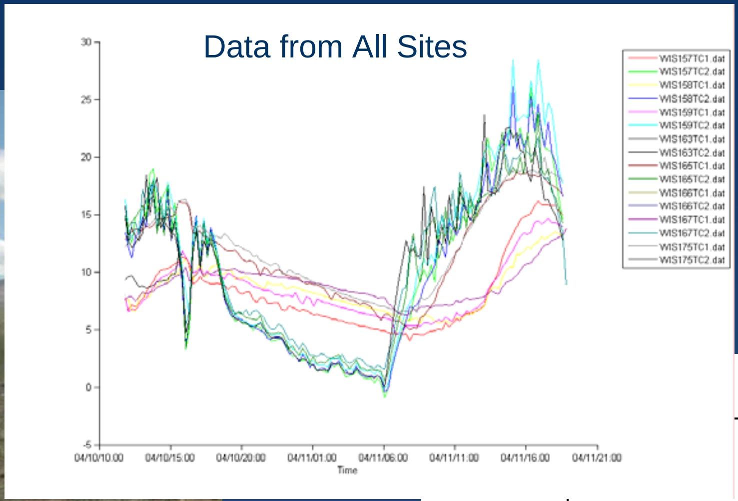
- One-wire bus

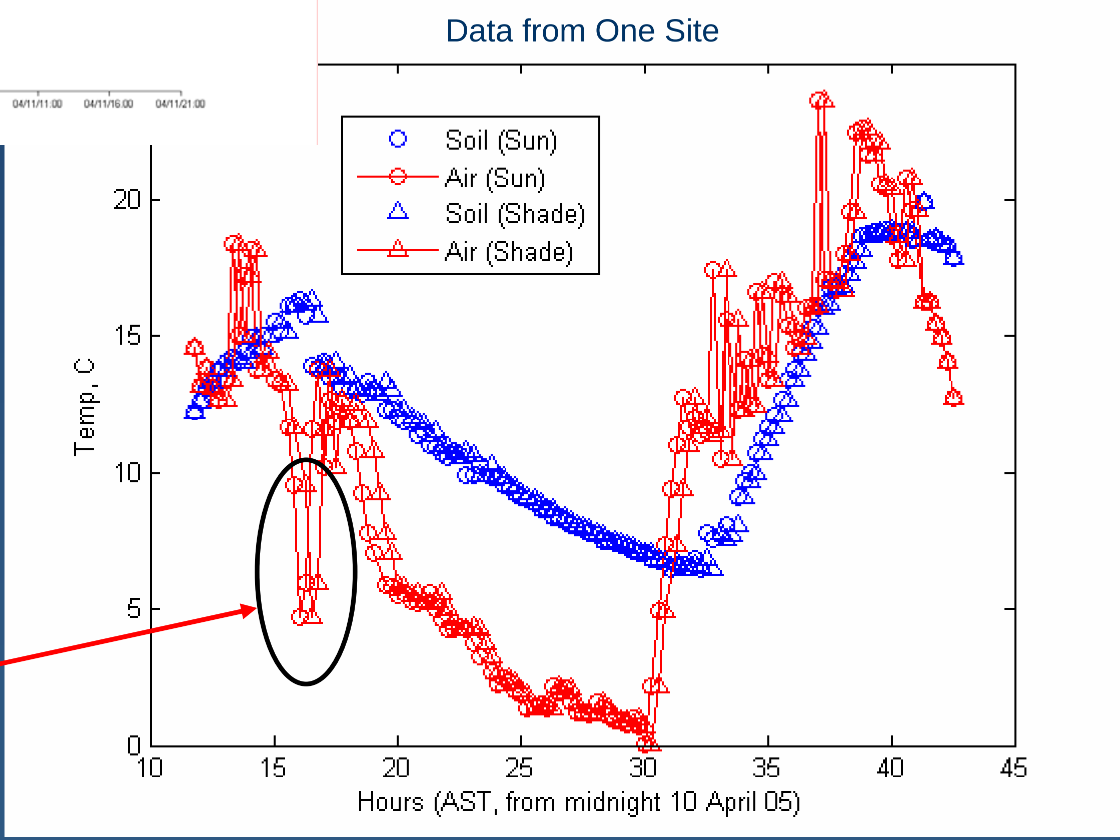
Provision for external energy supplies

- Supports autonomous switching between internal and external energy sources
- Battery-backed solar

Trial Deployment, April 2005: Grasslands site, C. Hart Merriam Elevational Gradient







Microburst and brief cloud cover

A few lessons learned so far…

- Packaging is a challenge
  - Weatherproofing vs. probe interfaces
- Probe costs are significant
  - Probeset costs will exceed sensor node costs
- Deployment is time-consuming
  - 3D space
  - Truly “embedded” probes
- Requirements for deployment will vary by site
- Data correlation radii vs. transmission range
- Maintenance and QA
  - Probe models in non-stationary environments

Dynamic Sensing of Ecosystem Processes

- motivating application: **revolutionize understanding of environmental change**
  - forecast how altered climate and CO_2 will impact biodiversity and carbon storage in the biosphere
- challenge: endow network with sufficient explanatory power under significant energy consumption constraints
- tight coupling between the sensed and the sensors
  - sensors are even more deeply embedded in their environments
  - only sense and communicate when you need to

Application Properties

- data is highly heterogeneous: natural scales range from
  - meters to landscapes
  - seconds to years
- systems are strongly non-linear and non-stationary
- motivates **dynamic model-driven control** of
  - sampling
  - communication
  - estimation and prediction
  - model inference

  according to their relative values and costs:

<u>integrate spatio-temporal sensing with modeling and prediction in an adaptive framework</u>

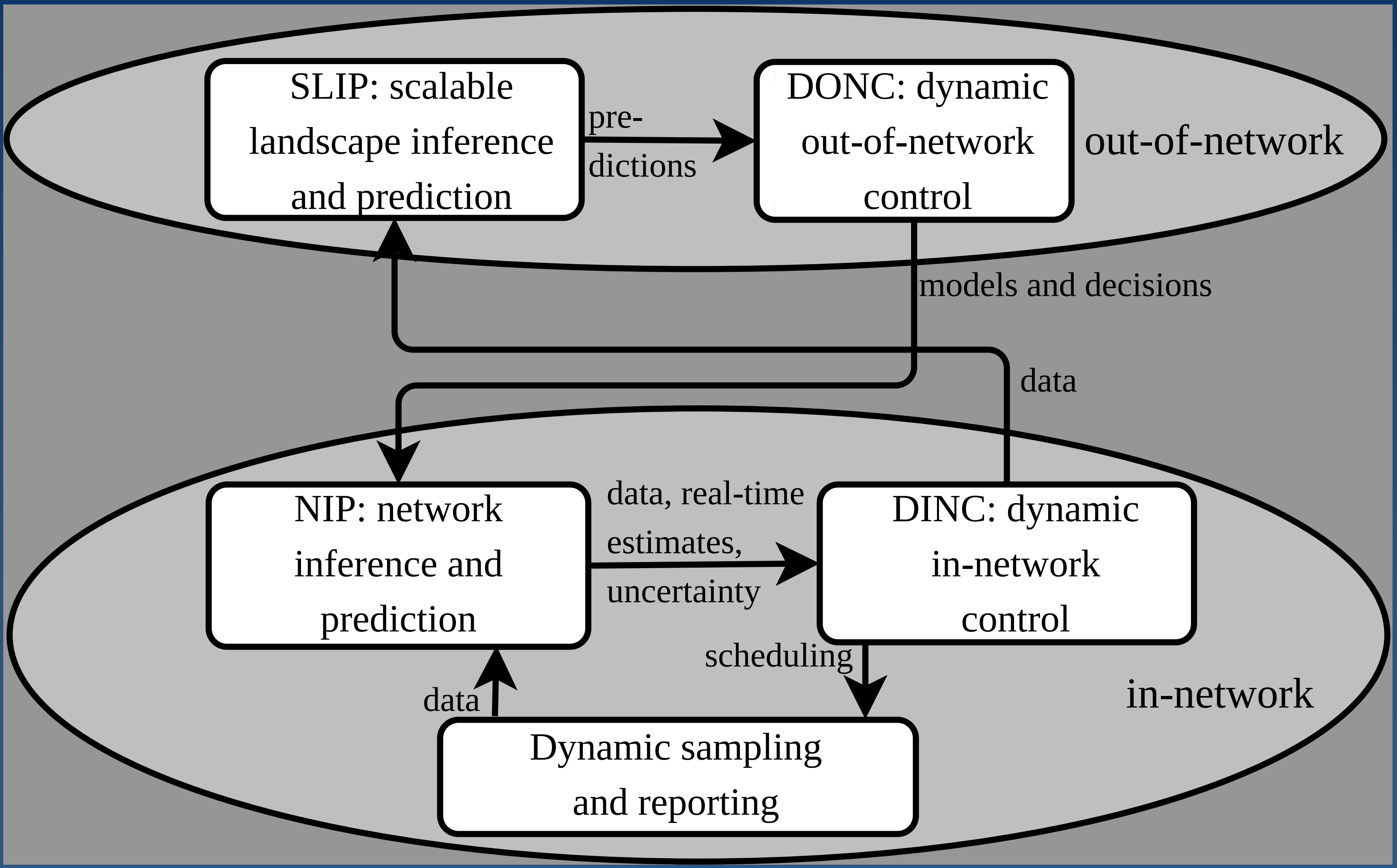
Architectural Properties

1. limited in-network resources
2. complementary out-of-network capability
   - relaxed energy constraints
   - massive processing power
   - latency

approach

- adaptive in-network joint estimation and coding
  (inner, fast control loop)
- supervisory out-of-network processing
  (outer, slow control loop) – model inference

Dynamic Sensor Networks: Components of Control



Model-driven sensor network activity

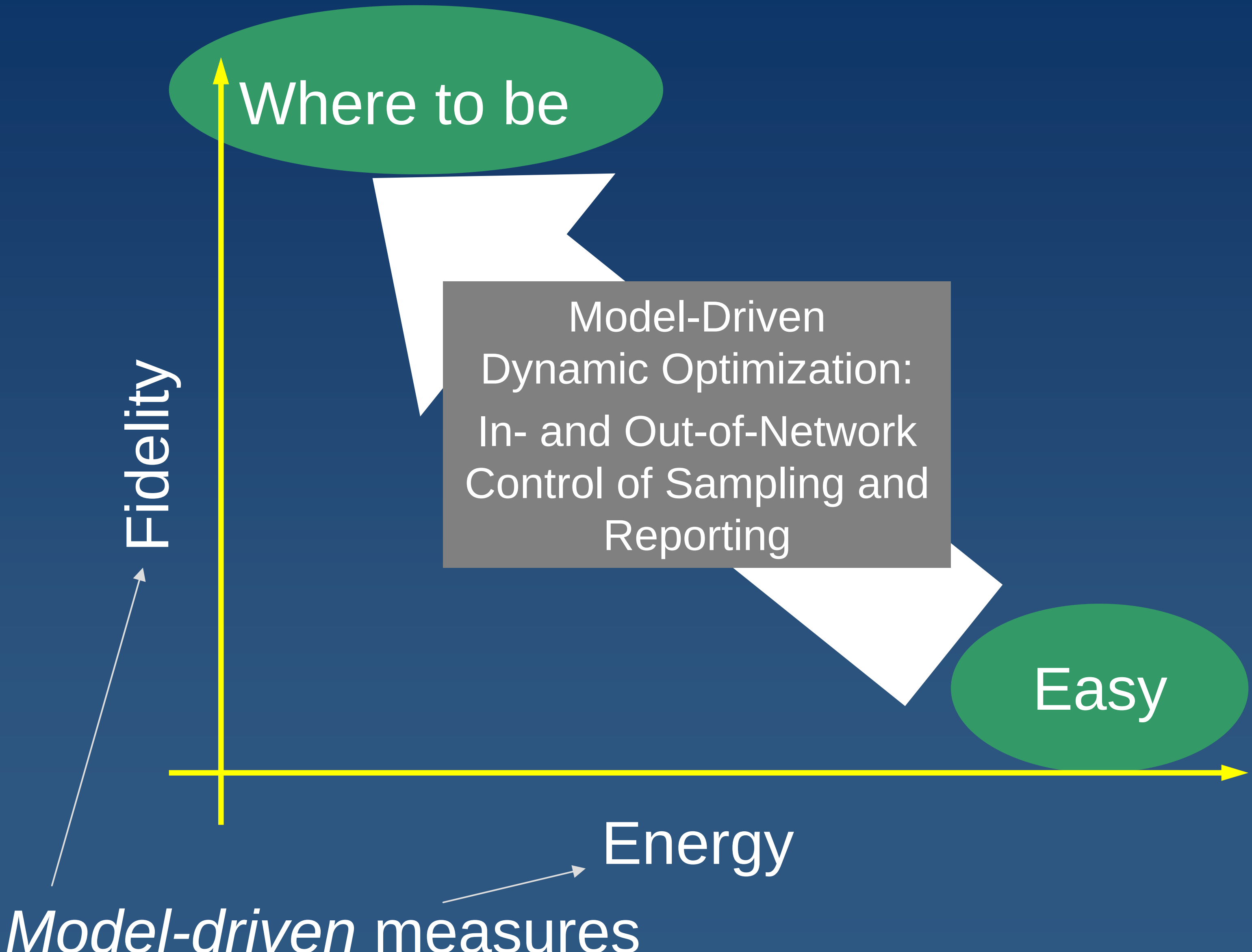
Modeling effort

- Model, measure, and control uncertainty as a function of cost
  - Hierarchical Bayes
  - MCMC

Data service component implementation

- coordinates the execution and adaptation of sub-plans and their interaction with WiSARDNet sensors and communication layer
- tags data with meta-data about sampling and measurement conditions
- provides multi-resolution data storage within the network

Goal: maximum predictive power *at ecological model level* for a given energy cost



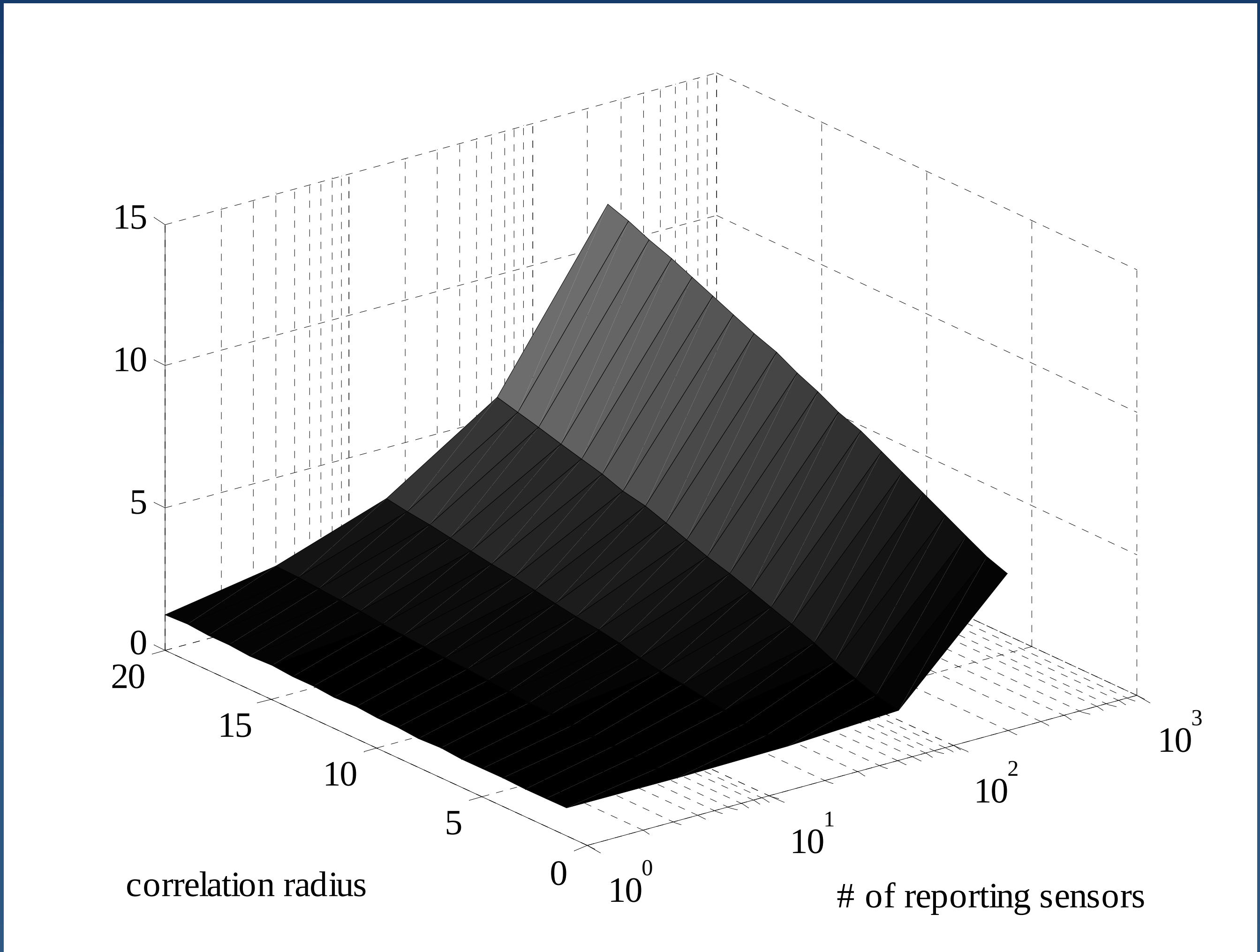
Working at the right level…

Example: multi-sensor time series of temperature.

<u>Can view as</u>

- streams of numbers
  - use general-purpose source codes (e.g., delta modulation)
- correlated spatio-temporal process
  - use a parameterized statistical model to drive adaptive space-time sampling and reporting
- high-level model input
  - sampling driven by the needs of, e.g., leaf efficiency/tree growth model; sampling rate may be high because of sensitivity of high-level model, even when dynamics appear slow

Example: Precision vs. # of reporting sensors: linear estimate of a sampled random field



Algorithmic challenges

- Finding good models to
  - trade fidelity (including latency) and cost
  - Explore power of dynamic algorithms
- Cross-layer run-time optimization framework
  - Multiple applications
  - Data services
    - Multi-resolution storage and communication
  - OS
  - Networking

Conclusion

- Can a dynamic sensor network deliver better results than fixed sampling and out-of-network modeling in the context of changing real-world environmental conditions?

- Understanding the biodiversity and carbon consequences of environmental change is a problem broad enough to encompass many of the types of challenges faced by DDDA systems.

- Results from these experiments will inform the design of accurate and energy-efficient production networks tailored to specific applications.
    - Micrometeorological sensing and nowcasting, pollution monitoring and environmental remediation, and public security/safety.