Next Generation Cyber-Physical Systems Utilizing RF-Powered Computing

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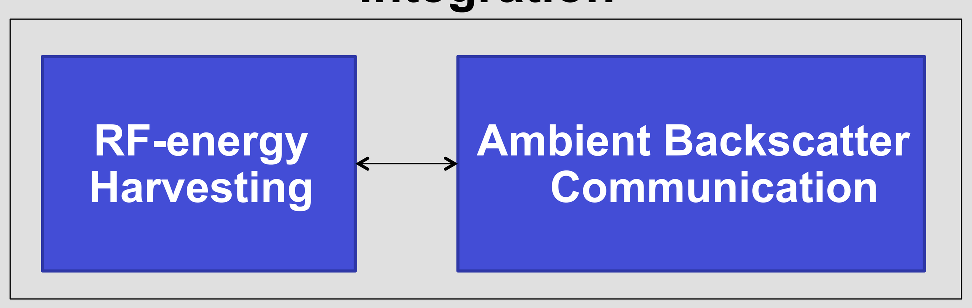
So What? Who Cares?

Motivation

- **Resilience** and **self-powered** are two critical requirements of future cyber-physical systems in various applications
- RF-powered computing bridges the gap between energy and performance by providing reliable and perpetual systems

Integration

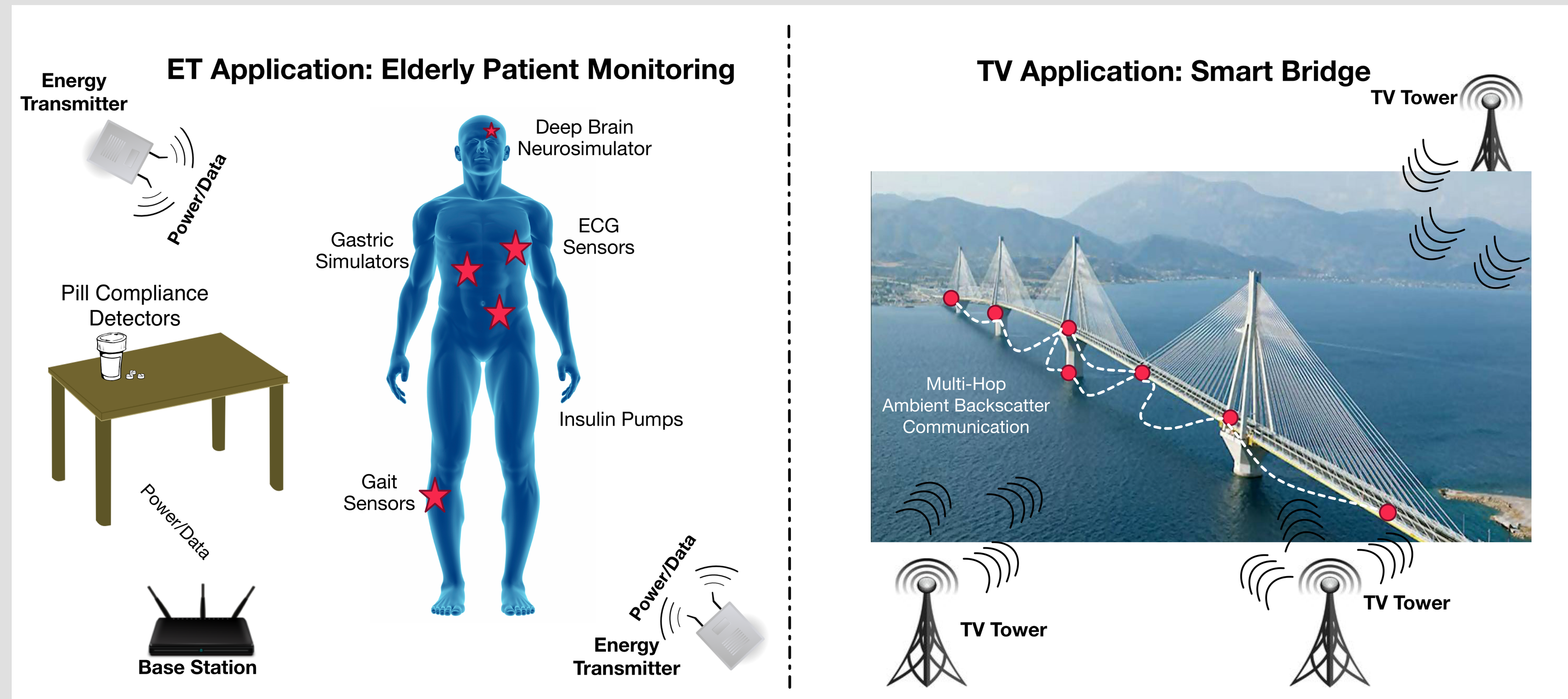


RF-Powered Computing

- **RF-energy harvesting:**
  - Convert RF radio signals to electricity
- **Ambient backscatter:**
  - Piggybacks the existing ambient RF signals for data communication

Initial Applications

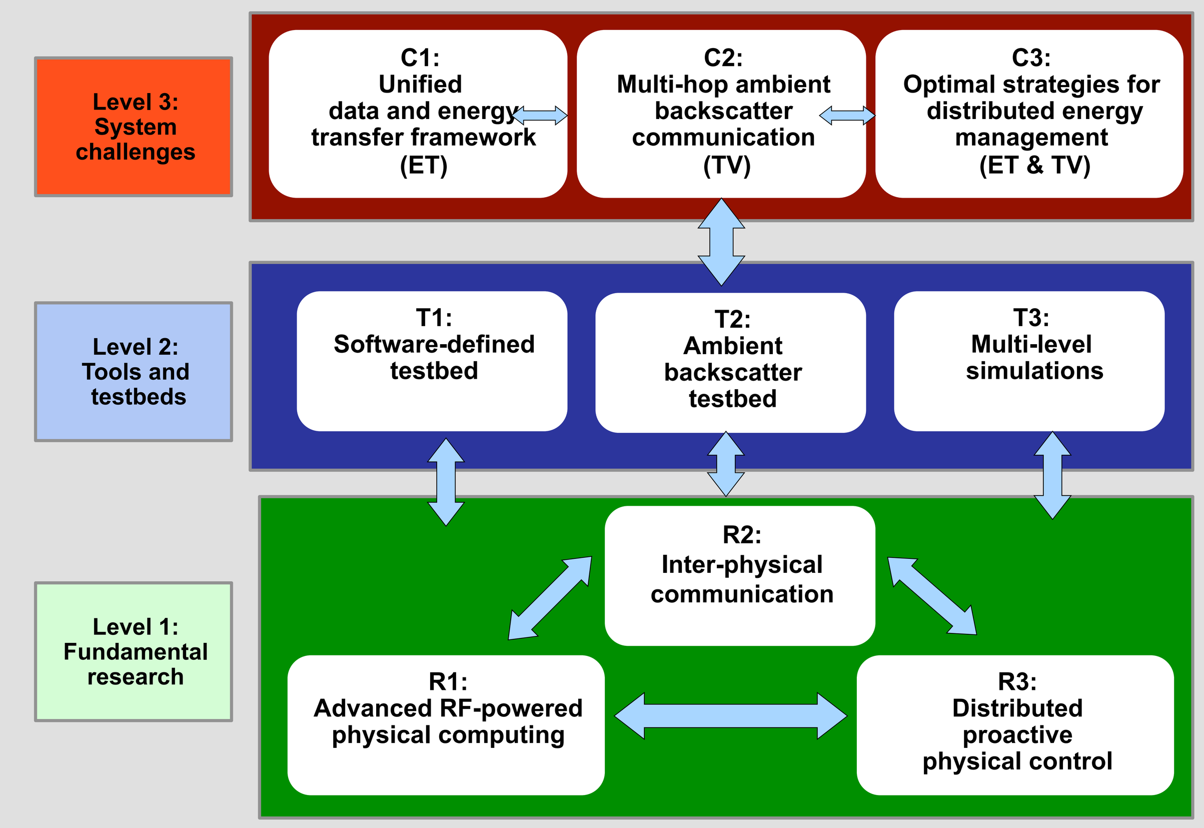
- RF-powered computing favors a wide range of applications, including: Healthcare, structural health monitoring, air pollution monitoring, and smart roads.



Two initial applications benefit from RF-powered computing

Three-level Strategic Plan

- The **System level** (top) defines our grand system challenges
- The **Testing level** (middle) validates research outcomes
- The **Research level** (bottom) defines our distinct thrusts



Tools and Testbeds

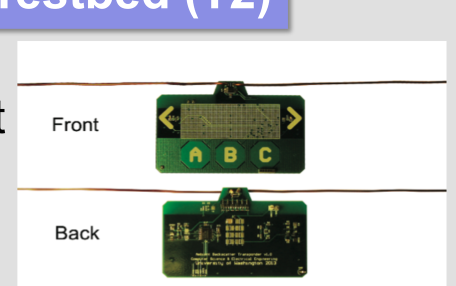
Software-defined Testbed (T1)

Architecture of Programmable Energy Transmitter

- Controllable energy transfer experiments perform through a set of programmable USRPs with WBX/SBX daughter-boards connected to adjustable power amplifiers
- Frequency, phase, time, and amplitude of energy waves are programmable
- Integrated data and energy transfer is achievable by utilizing MIMO expansion ports
- Powercast Powerharvester® Evaluation Boards used for harvesting RF waves

Ambient Backscatter Testbed (T2)

- Ambient backscatter experiments perform through a set of nodes (prototypes) capable of data transfer by piggybacking ambient TV signals

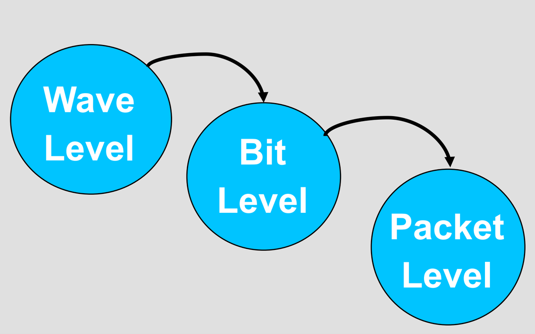


Ambient Backscatter Node

Multi-level Simulations (T3)

Simulink
ANSYS HFSS
MATLAB
Network Simulator (NS2)
Customized Simulator

- The proposed research thrusts need to be analyzed and evaluated at three levels:



Proposed Approach

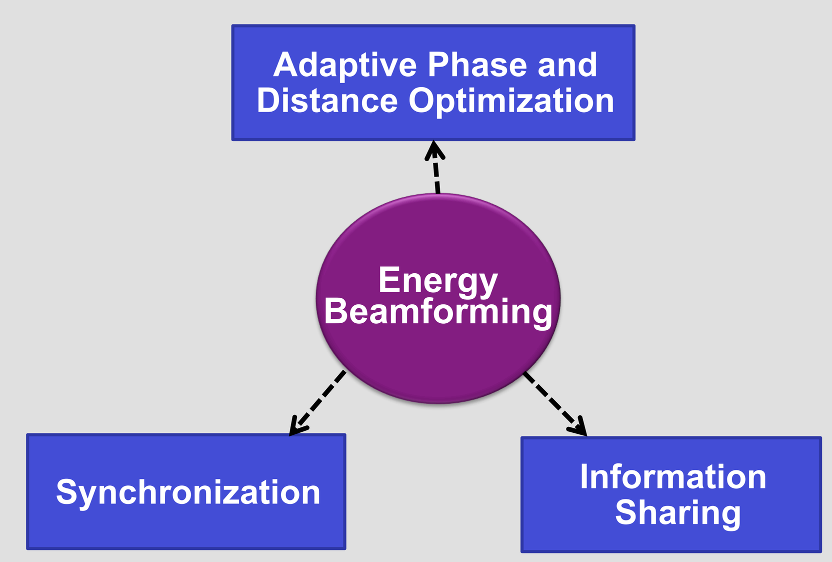
Advanced RF-Powered Physical Computing (R1)

Design and Analysis of Energy Waves

- Studying the efficiency and effects of these parameters on the optimal harvested power:
  - Energy pulse repetition frequency
  - Energy wave sample rate
  - Energy pulse duration and bandwidth
- Building software-defined energy transmitter and adaptive energy harvester circuit

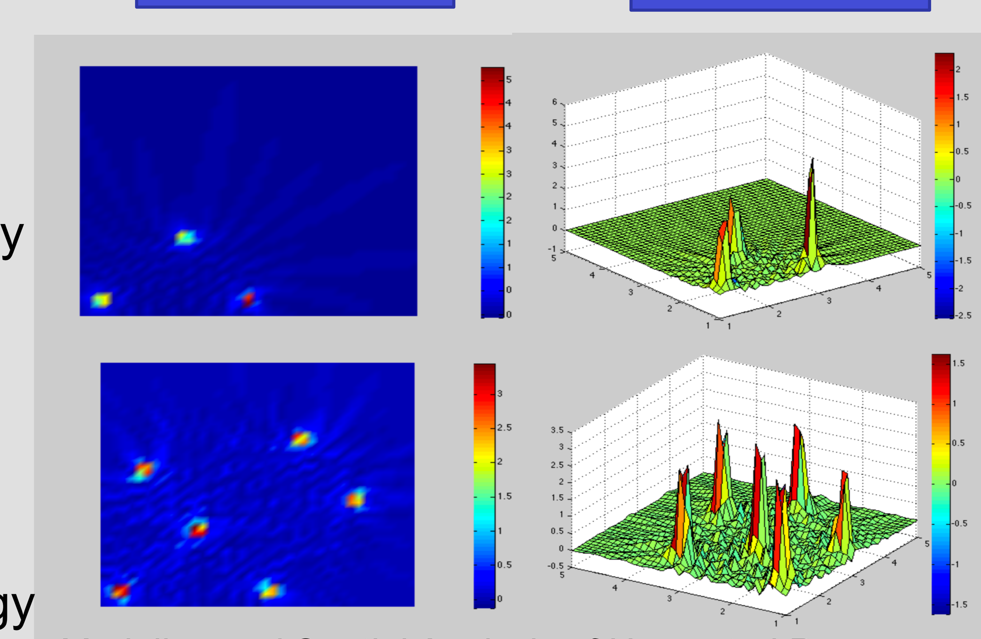
Distributed Energy Beamforming

- Align energy transfer phases and location of nodes to combine energy waves constructively at targets
- Adaptive time, phase, and frequency synchronization are the critical challenges
- Outcomes: Higher rate, range, and efficiency of energy harvesting



RF Energy Modeling

- For controllable energy transfer:
  - Model and analysis of the number of energy transmitters (ETs) and spatial spacing on harvested power
  - Model and analysis of energy interference
  - Analysis of target motion
- For ambient TV signals:
  - Spatial-Time analysis of available TV energy utilizing TV spectrum databases



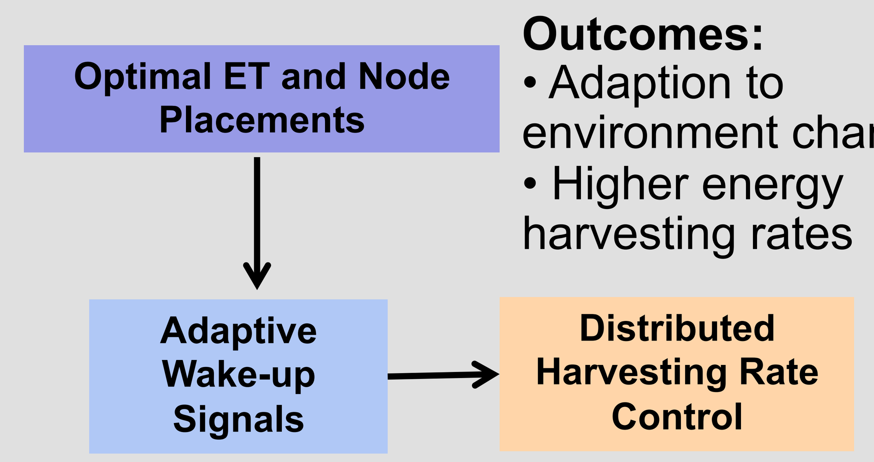
Modeling and Spatial Analysis of Harvested Power in Controllable Energy Transfer

Distributed Proactive Physical Control (R3)

Optimal Energy Management

- Optimal resource allocation through integrating **reinforcement learning** and **adaptive operational control** algorithms to guarantee resiliency
- Dual control problem of energy management while learning the dynamic of current state of the system and its anticipating evolution

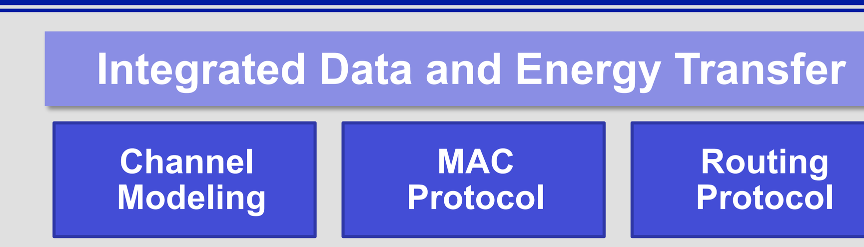
Topology Control



Outcomes:
- Adaption to environment changes
- Higher energy harvesting rates

Inter-Physical Communication (R2)

Integrated Data and Energy Transfer



- Unified energy and information transfer requires an extended channel model to characterize the maximum rates of power and data transfers
- Trade-off between energy and data communication functions requires a fresh perspective on MAC and routing protocol design
- Challenges:
  - How and when should the energy transfer occur, its priority and impact on data communication
  - How routes must be constructed to leverage spatio-temporal distributions of available power and ensure sufficient levels of energy along active data paths

Multi-Hop Ambient Backscatter Communication

- Extend the current single-hop ambient backscatter communication to multi-hop
- Requires routing metrics that utilize the best placed sensors under both statistical and deterministic TV channel activities
- Outcomes: network of autonomous backscatter nodes with high performance, resiliency, and orders of magnitude more energy efficiency

Acknowledgement

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References

[1] S. Gollakota, M.S. Reynolds, J.R. Smith, D.J. Wetherall, The Emergence of RF-Powered Computing, IEEE Computer Magazine, Jan. 2014, vol. 47, no. 1, pp. 32-39.

[2] S. Basagni, M.Y. Naderi, C. Petrioli and D. Spenza, "Wireless Sensor Networks With Energy Harvesting", in Mobile Ad Hoc Networking: Cutting Edge Directions, Chapter 20, John Wiley & Sons Inc., Hoboken, NJ, 2012.

[3] Powercast Corp., http://www.powercastco.com.

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