Next Generation Cyber-Physical Systems Utilizing RF-Powered Computing

Text
Yousof Naderi, PhD Student

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1 Background and Motivation (so what? who cares?)

This research proposes to develop an enabling framework for reliable and self-powered cyber physical systems (CPS) by utilizing RF-powered computing. RF-powered computing is an emerging technology in which small computing devices use ambient electromagnetic radio frequency (RF) waves from existing TV and cellular transmissions, and RF waves from controlled energy transmitters (ETs) for power and communication. In particular, devices use RF energy harvesting technology to convert RF radio signals to electricity by a rectifying antenna. In addition, they can communicate between each other through ambient backscatter technology, which piggybacks the existing ambient RF signals, rather than generating new radio waves, for orders of magnitude more energy efficient communication. RF energy harvesting technology can favor a wide range of applications in healthcare to remove the dependency of wearable sensors from battery usage. As an example, in indoor elderly patient monitoring, small lightweight wearable gait sensors can be perpetually powered by a nearby ET in order to detect, process, and report patient falling. On the other hand, smart bridge is an example for ambient backscatter technology where existing TV signals can be used for both power as well as communication to monitor the health of the bridge and detect the dangers.

2 Proposed Research

This research is structured around the three-level strategic planning approach. The top (Systems) level defines our grand challenges, which highlight the need to engineer a system that provide unified data and energy transfer, reliable multi-hop ambient backscatter communication, and optimal strategies for distributed energy management.

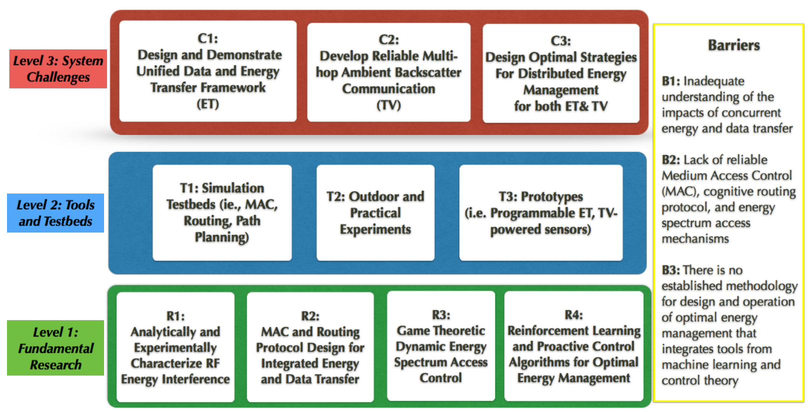

Figure 1: Proposed three-level strategic planning.

The first system challenge is a unified data and energy transfer framework. It indicates the need for protocols and algorithms to control and guarantee robust and non-invasive communications when energy and data signals transmit: a) in-band at the same channel, b) out-band concurrently at different channels, and c) combined together. The second grand challenge highlights the need for developing a novel multi-hop ambient backscatter communication in which each node forwards its received signals to the next node by utilizing backscatter technology and ambient RF signals. This enables autonomous network of ambient backscatter nodes. The third grand challenge highlights the need of optimal strategies for distributed energy management over the time. It is essential to provide optimal power transfer to all active devices while minimizing the energy interference.

The middle (Testing) level validates research outcomes using simulation testbeds, outdoor and practical experiments, and prototypes. Ultimately, the validated insights and tools will be applied to help address real world challenges at the top level. The system challenges articulated at the top level feed into the bottom (Research) level, which defines four distinct thrusts dealing with (i) characterizing energy interference, (ii) designing MAC and routing protocols, (iii) dynamic energy spectrum access control, and (iv) reinforcement learning and proactive control algorithms for optimal energy management.

The first, **Thrust R1**, will characterize analytically and experimentally RF energy interference. The high power wireless energy transfer from controlled power sources, in comparison to low-power data communications of devices, can cause severe interference, reduce communication reliability and throughput. Currently there is no study on the impacts of concurrent energy and data transfer in low-power devices. This thrust will take a systematic experimental study to understand the impacts of wireless energy interference on the packet delivery performance and the distributions of received interferer power in CPS. It will study the effects of energy and data frequency separations, and identify their dynamics. This thrust will also derive analytical models for energy interference which captures both constructive and destructive interferences resulting from multiple power sources. **Thrust R2** is focused on development of medium access control (MAC) and routing protocols for integrated data and energy transfer. In particular, the tradeoff between energy and data communication functions requires a fresh perspective on MAC protocol design for appropriately sharing the channel. The challenges include how and when should the energy transfer occur, its priority over, and the resulting impact on the process of data communication. The challenges in aggregating the charging action of multiple power sources, raises questions on how routes must be constructed to ensure nodes along a path harvest sufficient levels of energy, how the controllable power sources must be placed to facilitate efficient energy transfer. We propose a joint routing and energy-scheduling mechanism to address these challenges. When ambient TV signals serve as power sources, we will explore routing metrics that utilize the best placed sensors under both statistical and deterministic channel activities. Moreover, we will extend the current single-hop ambient backscatter communication to multi-hop for establishing network of autonomous nodes with high performance and resilience to power shortages. **Thrust R3** is focused on developing a game theoretic dynamic energy spectrum access by intelligent transmission and harvesting of energy streams over a range of frequencies, thereby exploiting the multi-band frequency accommodation of RF energy harvesters and allowing wireless power sources and devices to adaptively allocate and use the data and energy frequencies. The final **Thrust R4** is focused on the optimal resource allocation through reinforcement learning and adaptive operational control algorithms. The focus on this stage is on distributed energy transfer and harvesting management over the time. The devices need to rapidly reconfigure their resources to maintain the quality of operation, and data and energy transfer rate need to be control intelligently. A key characteristic of these problems is the lack of centralized information for decision making, and the dynamic of environment that affect both energy management and data transfer. This is a dual control problem of energy management while learning the dynamic of current state of the system and its anticipating evolution. We will investigate techniques for providing the guaranteed performance and resilience to environment changes.

3 Potential Impacts

Integrating RF-powered communication and computing into physical systems is vital for reliability, performance, and robustness of future CPS technologies. It promises to embed computing into the everyday world in ways that were previously infeasible. It uses the controlled and existing ambient RF signals as leverage for both power and communication. This research has potential impacts on a wide range of applications including healthcare and infrastructure monitoring.

In the case of elderly patient monitoring, the main impact is enabling perpetual lifetime for wearable sensors such as gait and heart monitoring sensors, which is otherwise infeasible. Moreover, the proposed unified data and energy transfer improves the reliability and resiliency in continuous vital information reporting. For smart bridge, the proposed research utilizes ambient TV signals to enable autonomous independent monitoring system, by which a network of sensors is realized by multi-hop ambient backscatter to monitor the health of the bridge. Finally, the proposed distributed energy management strategies guarantee efficient operation of cyber-physical system through optimal RF energy harvesting and transfer during the system operation.