Cross-Layer Energy Optimization for IoT-Enabled Smart Spaces

Nailah Saleh Alhassoun
Department of Computer Science
University of California, Irvine
Supervised by Nalini Venkatasubramanian
nailah@uci.edu nalini@ics.uci.edu

***Abstract*—Perpetual IoT systems are essential to many safety and mission-critical applications, e.g. assisted living, healthcare and public safety, which are characterized by continuous monitoring (24/7) and ubiquitous sensing. While IoT-enabled many applications and services, several limitations arise in operating IoT deployments in a resilient manner over time; challenges include the energy cost and constraints. In our research, we aim to handle energy challenges caused by perpetual operations in each level of the system architecture (device, communication, and processing). We use a semantic approach that utilizes context of extracted activities of daily living (ADLs) and indoor space-state (normal, anomaly, and emergency) to drive energy optimized sensor activations. In addition, we are uniquely leveraging features such as: heterogeneity of IoT devices (wearable, ambient, and vision) in terms of: energy cost, energy source (battery-operated and wall-powered IoT devices), processing capability, mobility, communication technologies and transmission protocol (NB-IoT, LTE-M, LoRa, Wi-Fi, 4G/5G, Bluetooth, Zigbee, etc.), processing location (device, edge, could). To validate our approach, we developed an elderly fall detection system using multi-personal and in-situ sensing IoT devices derived from real-world deployments; using our measurements to drive larger simulations. We show that our proposed algorithms such as, Cost-Function-Gradient can achieve greater than 4X reductions in energy dissipation and doubling system-lifetime without loss of sensing accuracy.**

I. MOTIVATION

The Internet of Things (IoT) revolution holds significant intelligent promises to improve the quality of life. It is considered to be a key technological enabler towards the realization of smart cities, communities, and homes. Every second, 127 new things are connected to the Internet, Cisco predicts there will be 500 billion devices connected to the Internet by 2030. The growth is a result of the increasing installations of IoT systems that offer diverse applications/services. Smart home sensing systems have created the capability to automatically and unobtrusively collect information and provide value-added services derived from this information; which has provided a promising opportunity to build powerful and perpetual systems.

Perpetual awareness systems are sensing systems characterized by continuous monitoring; they are essential to many smart spaces' applications, such as in the assisted living context and public safety.

The success of these IoT platforms depends heavily on a robust middleware managing the complexity of sensors, devices, and data continuously. However, several challenges arise in operating IoT deployments in resilient manner over time. First, IoT devices typically are small in size with resource constrained nature in terms of limited processing power, battery and storage capability. Secondly, the need for low cost and mass-scale production further enhances the likelihood of component variability and structural failures. Third, the diversity of settings and deployments play an important role in both the accuracy and cost of the applications deployed. Lastly, some IoT-based applications are expected to operate 24/7, i.e. perpetually, to monitor, deliver services and detect events this raises issues of the cost of operation and continuous energy consumption.

One relevant use-case of IoT-based mission-critical and perpetual awareness application is smart home security system that can assist those with disabilities, vision impairments, deaf and hard of hearing, by capturing anomalous events and intrusions, then providing alerts in the event of suspicious movement. Another relevant use case is elderly fall detection; fall detection is a major challenge in the public health care domain – the Center for Disease Control reports over 2 million falls annually in the United States. The design of reliable systems to quickly detect and mitigate the effects of falls will help improve outcomes significantly.

We were motivated by the smart community project SCALE [1]; that has been deployed in the Victory Senior Housing facility in Montgomery county, MD; for a wide variety of sensing applications. One of these applications is SAFER [2, 3]; a personal sensing for safety. SAFER is a heterogeneous IoT test-bed; deployed in homes to detect critical events, such as injuries and falls that must trigger immediate action and response. Through the elderly fall detection system, we recognized the continuous energy cost, plus that battery-powered devices such as mobile and wearable sensors dissipate power quickly and need to be recharged.

A key challenge here is the energy consumption associated with perpetual operations. Therefore, in this research we propose a novel cross-layer energy-aware IoT framework for perpetual systems. Our semantic approach utilizes the indoor context, such as: activities of daily living (ADLs) and indoor space-state (normal, anomaly, and emergency). Also, it is uniquely leveraging the heterogeneity of IoT devices, communications and processing while IoT devices co-execute to ensure safety of occupants.

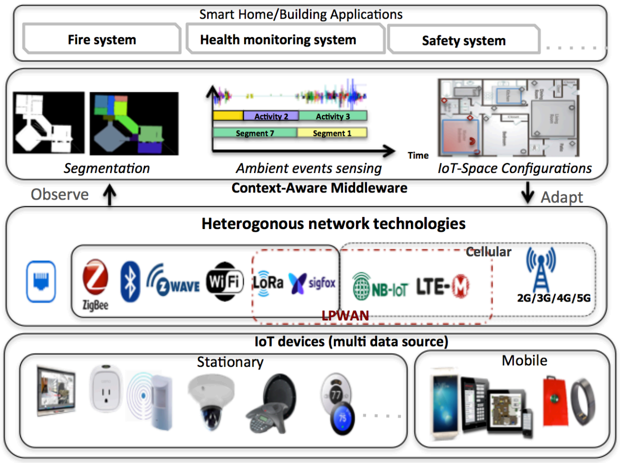

Fig. 1: Three-phase architecture

II. Towards Energy Efficiency and Perpetual IoT Platforms

The energy efficiency problem is characterized in indoor context where heterogeneous IoT devices have varying capabilities, such as wearable, ambient, and vision. Our experience in operating and maintaining IoT systems in real-world test-beds indicates that exploiting real-time semantics with the heterogeneity nature of IoT devices is a promising approach to increase the perpetually and sustainability of IoT platforms.

Knowledge of the device capabilities, transmission and processing options can also be used to enable long-term operations while meeting accuracy threshold demands. We explore our solution within the context of perpetual sensing and operations in smart spaces to address major research problems regarding sensors' configuration scheduling/activation, IoT multi-network provisioning, quality-aware processing, failure/privacy techniques' constraints.

We proposed a three-phase middleware, as shown in Figure 1, framework to handle this complexity that arises due to dynamic nature and diversity of the underlying ADLs, spaces and IoT devices [2]. In [3] we formalize the energy efficiency problem for heterogeneous IoT devices as a constrained optimization problem (proven to be NP-hard).

Also, we introduced dynamic configuration algorithms that control the IoT networks and to compute the near optimal overall energy configuration. For instance, Cost-Function-Gradient (CFG) algorithm, extends the battery capacity 2–4 times by reducing the energy consumption of the IoT devices by utilizing the space semantics (ADLs) and choosing efficient configurations for devices, as shown in Figure 2. In addition, we proposed network provisioning algorithms based on different available IoT connectivity options, such as cellular (2G/3G/4G/5G), Low Power Wide Area such as (NB-IoT, LTE-M and LoRa), Wi-Fi, Bluetooth, Zigbee, etc. each communication technology associated with different bandwidth, transmission range, energy cost, latency reliability, and network-management features. The application factors such as range, data requirements, latency and space context shifts between multiple space-state (normal, anomaly and emergency) this will dictate the choice of one or some form of combination of networking technologies.

In this research, we aim to enable and ensure the multiple functional and non-functional needs of societal scale applications by leveraging new emerging technologies - this will require an in-depth understanding of how these requirements interact. Therefore, we are considering a scientific methodology in our research by implementing a real test-bed to carry out measurements and gain insight. We built an elderly multi-sensor fall detection system's SAFER, which provides us with a real-world implementation of smart assisted living IoT systems where we run algorithms, derived energy and accuracy measurements. Then for scalability, we conducted further experiments by creating test-cases at different scales based on real-world data, run our measurements/outcomes to discrete-event simulator, which indicated that the proposed algorithms were able to create an energy-efficient system that extended the system-lifetime while maintaining services' qualities.

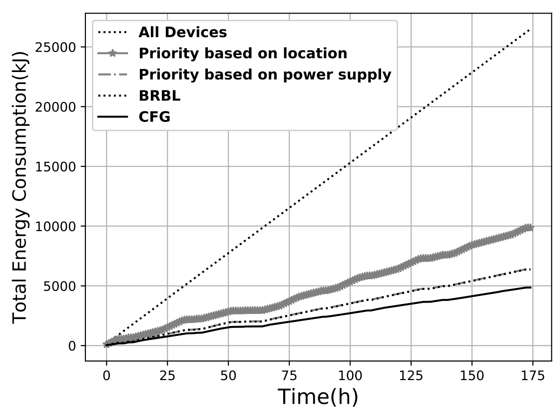

Fig. 2: Comparison of IoT platform algorithms to show total energy consumption, CFG algorithm saves 80%

Acknowledgment

I would like to thank my advisor prof. Nalini Venkatasubramanian for her continuous guidance and support.

References

[1] M. Y. S. Uddin *et al.*, "The scale2 multi-network architecture for iot-based resilient communities," in *IEEE International Conference on Smart Computing*, 2016, pp. 1–8.

[2] N. S. Alhassoun, M. Y. S. Uddin, and N. Venkatasubramanian, "Safer: An iot-based perpetual safe community awareness and alerting network," in *2017 Eighth International Green and Sustainable Computing Conference (IGSC)*, Oct 2017, pp. 1–8.

[3] N. S. Alhassoun, M. Y. S. Uddin, and N. Venkatasubramanian, "Context-aware energy optimization for perpetual iot-based safe communities," *SUSCOM*, vol. 22, pp. 96–106, 2019.