BASHIMA ISLAM | RESEARCH STATEMENT

My research focuses on enhancing **time-sensitive** and **inference** capable batteryless **mobile computing** devices; and addresses the growing need for **sustainable sensing** and **control solutions**. Advancement in batteryless and energy-constrained systems is necessary to realize continuous and pervasive sensing as battery replacement is cumbersome and hard to scale. To illustrate, even with a battery life of 10 years, when the number of IoT (internet of thing) devices reaches one trillion by 2035 [20], we will replace 274 million [21] batteries daily. While existing works on batteryless computers primarily concentrate on harvesting units, real-time clock, intermittence management, and memory management (Fig 1), their timeliness, data-processing efficiency, self-adaptation, and user interactions are still unexplored. Without time-sensitivity and an efficient processing layer, these systems fail to capture and process data within the deadline and generate irrelevant and ineffective results. It makes batteryless systems unsuitable for a wide range of necessary applications, from infrastructure monitoring to wildlife tracking, medical implants, and long-term health monitoring. For example, the long-life and low maintenance of batteryless systems make them perfect for tracking endangered wildlife (e.g., IBM's Project Rhino [23] monitors a herd of impalas for early rhino poacher detection). However, such a system is futile if it fails to notify the forest rangers before the poachers reach the rhino. Besides, these extreme edge devices require sophisticated inference and self-adaptation techniques for accurate and relevant outcomes. Moreover, application-specific constraints, user interaction, and programmability play a crucial role in their usability and integration.

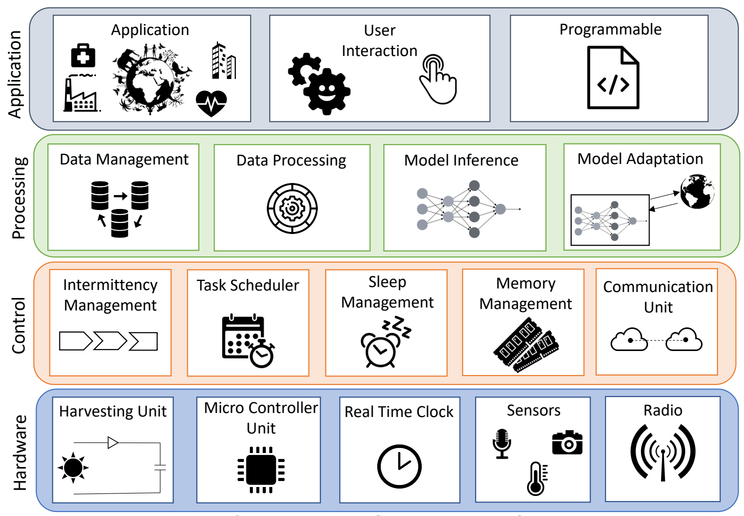

Fig 1. Architecture of Batteryless Sensing and Computing Devices

I focus on the *intersection of systems and machine learning* and ensure timely response in batteryless systems while maintaining high output quality by focusing on the *control* and *processing* layers (Fig 1). My research was the first to propose **adaptable machine learning approaches for time-aware ultra-constrained and intermittently powered hardware**. I achieve this using a two-step approach: (1) *understand the physical phenomena and unique characteristics of the application domain* (e.g., studying harvestable energy patterns and expressiveness of deep features) and (2) *develop novel frameworks that leverage application-specific characteristics*. Besides designing novel frameworks for batteryless systems, my research explores the sensing potential of resource-constrained devices in various application domains, including computer vision [5, 8], healthcare [11, 12], personal assistance [10], pedestrian safety [9], and infrastructure monitoring [5, 4, 7, 13], with a vision to merge these two paths in the future. For this exploration, I worked with experts from academia and industry, including Columbia University, Samsung Research America, Nokia Bell Labs, and UNC School of Medicine. My works have appeared in top-tier Computer Science venues, including **UBICOMP**, **IPSN**, **RTAS**, and **MobiSys**. As recognition of my work, I was named a finalist of the **Borriello Student Award** at UbiComp 2020 and was selected for the **Rising Stars** in EECS 2020.

Life-long sensing and learning are the future of computing, demanding intelligent, programmable, and sustainable edge computers. Batteryless systems last forever in principle (as long as the energy harvesting conditions are favorable), and so, they are the perfect candidates to realize this future. My Ph.D. research has only scratched the surface of this challenging and exciting field. I hope to drive this discipline forward by focusing on augmenting batteryless edge devices' intelligence and calibrating them to solve real-world problems, e.g., remote healthcare, wildlife preservation, and climate change. My work will introduce *a new set of sustainable edge computers that are time-aware, inference capable, self-evolving, programmable, personalized, and user-friendly (Fig 2)* by contributing to all the batteryless device architecture layers (Fig 1). The interdisciplinary nature of my future works will present numerous collaboration opportunities inside and outside the department.

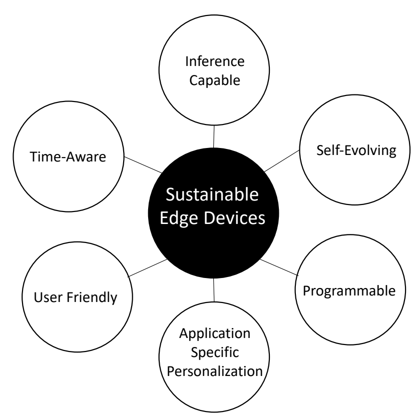

Fig 2. Future Sustainable Edge Devices

Time-Aware Computing on the Extreme Edge

Batteryless systems go through sporadic power on and off phases due to intermittently available energy; thus, they are called *intermittent systems*. Unfortunately, this intermittence in power supply hinders the timely execution of tasks and limits such devices' potential in certain application domains, e.g., healthcare, live-stock tracking. Unlike prior work on time-aware intermittent systems that focuses on timekeeping [14, 15, 16] and discarding expired data [17], my research concentrates on finishing task execution on time. I leverage the data **processing** and **control** layer of batteryless systems (Fig 1) by developing frameworks that (1) integrate energy harvesting and real-time systems [1, 2, 3], (2) rethink machine learning and computer vision algorithms for imprecise computing [2, 5], and (3) utilize distributed systems that collaboratively emulate a persistently powered system. By adopting this interdisciplinary approach, I have a unique perspective to devise impactful research questions involving system-level problems and application domain-specific prerequisites. In the future, I plan to expand my scope of research to the application layer of batteryless devices (Fig 1).

1. ***Deadline-Aware Scheduler for Intermittent Systems***. Batteryless systems rely on sporadically available harvestable energy. For example, kinetic-powered motion detector sensors on the impalas can only harvest energy when the impalas are moving, which cannot be ascertained in advance. This uncertainty poses a unique real-time scheduling problem where existing real-time algorithms fail due to the interruption in execution time. To address this, I developed Celebi [1], which considers the dynamics of the available energy and schedules when to harvest and when to compute in batteryless systems (Fig 3). Using data-driven simulation and real-world experiments, I showed that Celebi significantly increases the number of tasks that complete execution before their deadline when power was only available intermittently.

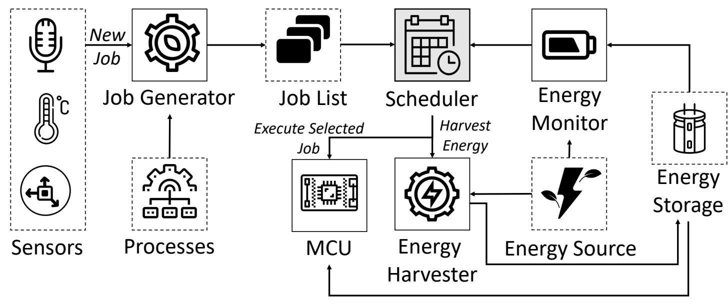

Fig 3. Celebi Overview

2. ***Imprecise Deadline-Aware Intermittent Systems***. Although Celebi increases the number of timely executed tasks, it disregards the impreciseness of many real-world complex workloads, i.e., they can achieve the desired outcome after only partial execution. In the rhino poacher example, the goal is to notify the rangers in time by trading off minimal accuracy. I proposed Zygarde [2]- an energy-aware and outcome-aware soft-real-time imprecise deep neural network (DNN) task scheduling framework for intermittent systems (Fig 4) Zygarde leverages the semantic diversity of input data and layer-dependent expressiveness of deep features and infers only the necessary DNN layers based on available time and energy. I further explored the impreciseness of real-world workloads by discarding redundant data points in mobile 3D reconstruction using additional sensors [5].

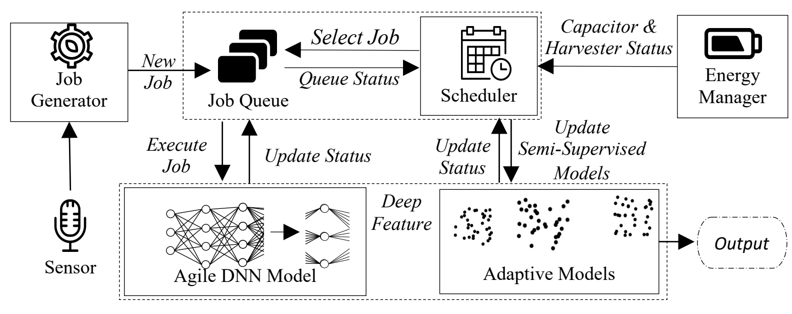

Fig 4. Zygarde Framework

3. ***Persistent System Emulation with Distributed Intermittent System***. Despite the efforts on improving deadline-aware intermittent systems, they miss target events during a power failure. This drawback limits intermittent systems' potential in continuous monitoring and fault-intolerant applications, e.g., respiratory disease monitoring [19], which affects more than a billion people every year [22]. The dynamic and uncontrollable nature of most harvestable energy sources hinders intermittent nodes from guaranteeing target event sensing and timely execution. To address this, I am exploring the potential of multiple intermittent systems (e.g., 15-100 impalas in a herd). I am currently developing FALINKS, where multiple intermittent nodes collaboratively go through wake-up and sleep sequences to imitate the sensing and computing capability of a single, persistently powered sensor node.

Future Directions

The future of computing will reshape how everyday objects will behave and influence human life by continuously learning human behavior, action, and environment. These everyday objects will beneficiate healthcare, environment monitoring, wildlife tracking, agriculture, and infrastructure maintenance. They will require life-long sensing and computing while having a small footprint, long life, and easy maintenance. My research seeks to develop these sustainable tiny computing systems by bringing out batteryless IoT devices' full potential. I aim to use them to design "deploy and forget" medical wearables and implantable that will continuously monitor health biomarkers. Another goal focuses on biodiversity and environmental preservation by the large-scale remote deployment of "never dying" self-sufficient sensor systems. I will split my effort into three directions -- (1) integrate artificial intelligence and machine learning with batteryless systems; (2) make batteryless systems adaptive to domain-specific needs; and (3) study the usability and impact of intelligent intermittent systems on the users. My future research will address high impact topics (e.g., remote health, biodiversity, urban infrastructure, and environment) and inspire multidisciplinary collaboration.

My future vision of sustainable IoT aligns with the National Science Foundation's (NSF) *Smart and Connected Communities'* roadmap, where NSF plans to dedicate 43 million USD. NSF *Cyber-Physical Systems* (CPS) recently awarded more than a million US dollars for the batteryless sensors for green infrastructure and calls for more proposals on sustainable sensing and computing systems for green infrastructure and precision agriculture. *Smart and Connected Health* (SCH), involving NSH and NIH, concentrates on pervasive computing and sensor integration to mobile health, which fits my vision of sustainable and user-friendly continuous health monitoring systems. Besides, NSF *Computer and Information Science and Engineering* (CISE) is another potential funding source for my future projects, especially their recent "*Next Generation of Sustainable Digital Infrastructure*" program.

1. Integrate Artificial Intelligence with Intermittent Systems. The advancement in the intermittent systems has mostly emerged from the programming language and system architecture perspectives. However, the opportunities that lie within exploring different core machine learning algorithms for optimized performance are still unexplored. I have started investigating this avenue with my work, Zygarde [2], where I proposed adaptive convolution neural networks for intermittent systems. I want to optimize different deep neural network architectures, such as residual networks and inception networks, for intermittent systems. Such optimization will enable the inference of countless existing machine learning algorithms in tiny intermittent systems. Besides optimization, I aim to explore *neuromorphic computing* for intermittent systems. Moreover, I see the vast potential of *self-supervised learning*, *active learning,* and *federated learning* in intermittent systems that will utilize the massive data sensed by these lifelong devices to their maximum potential. I have already taken the first step to explore this route during my Ph.D. [2, 3], and I aim to continue this walk as a faculty member.

2. ***Adapt to Domain-Specific Necessities***. I aim to extend the application of intermittent systems, which brings a new set of challenges from both the application domain and the batteryless domain. I foresee myself working in collaboration with experts in other disciplines like health and medicine and develop self-powered sustainable ubiquitous, and wearable sensing and feedback systems to support healthcare and wellness. One of my research goals is to collaborate with the experts in agriculture and environmental science; and develop a network of distributed batteryless intelligent computers for smart agriculture and biodiversity preservation by exploring distributed intermittent systems, opportunistic networking, hybrid architecture, and organic energy sources, e.g., microbial fuel. This research will present numerous collaboration opportunities with various faculties in the department. My short-term goal is to take my experience in respiratory monitoring [15, 16], HVAC maintenance [13], and pedestrian safety [9] one step further by investigating the requirements. I will collaborate with different reputed departments and research institutes at the University.

3. ***Study Usability and Impact***. My research goal involves developing novel intermittent systems to improve human lives. For achieving this goal, understanding human needs and their perspective towards these developed systems is required. Thus far, no literature exists on understanding human perspective or studying human interaction with intermittent systems. For example, an intermittently powered, continuous blood sugar monitoring system will be hugely beneficial for a large population, and how this population interacts and trusts such wearables has a high impact on their

health. I plan to collaborate with behaviorists and human-computer interaction (HCI) experts. Through these collaborations, I aim to perform detailed studies on the user experience, domain specifications before and after the development and deployment stages. It will pave the path to develop practical and impactful intermittently powered systems for our society and environment. This direction of my research will build a connection between human-computer interaction and batteryless systems. I am excited and committed to bringing together both sides' efforts to make intermittent systems have an immediate and lasting impact on the real-world.

REFERENCES

[1] *Bashima Islam*, and Shahriar Nirjon. 2020. Scheduling Computational and Energy Harvesting Tasks in Deadline-Aware Intermittent Systems. IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS). 2020.

[2] *Bashima Islam*, and Shahriar Nirjon. 2020. Zygarde: Time-Sensitive On-Device Deep Inference and Adaptation on Intermittently-Powered Systems. : Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies. September 2020.

[3] Seulki Lee, *Bashima Islam*, Yubo Luo, and Shahriar Nirjon. 2020. Intermittent Learning: On-device Machine Learning on Intermittently Powered System. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*. 2019.

[4] *Bashima Islam*, Md Tamzeed Islam, Jasleen Kaur, and Shahriar Nirjon. LoRaIn: Making a Case for LoRa in Indoor Localization. In *2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*. IEEE, 2019.

[5] *Bashima Islam*, Md Tamzeed Islam, and Shahriar Nirjon. Glimpse. 3D: A Motion-Triggered Stereo Body Camera for 3D Experience Capture and Preview. *2018 17th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*. 2018.

[6] *Bashima Islam*, Mostafa Uddin, Sarit Mukherjee, and Shahriar Nirjon. Rethinking Ranging of Unmodified BLE Peripherals in Smart City Infrastructure. In *Proceedings of the 9th ACM Multimedia Systems Conference*. 2018.

[7] Md Tamzeed Islam, *Bashima Islam*, and Shahriar Nirjon. Duty-Cycle-Aware Real-Time Scheduling of Wireless Links in Low Power WANs. In *2018 14th International Conference on Distributed Computing in Sensor Systems (DCOSS)*. IEEE, 2018.

[8] Chong Shao, *Bashima Islam*, and Shahriar Nirjon. Marble: Mobile Augmented Reality using a Distributed BLE Beacon Infrastructure. In *2018 IEEE/ACM Third International Conference on Internet-of-Things Design and Implementation (IoTDI*. IEEE, 2018.

[9] Daniel de Godoy, *Bashima Islam*, Stephen Xia, Md Tamzeed Islam, Rishikanth Chandrasekaran, Yen-Chun Chen, Shahriar Nirjon, Peter R. Kinget, and Xiaofan Jiang. Paws: A Wearable Acoustic System for Pedestrian Safety. In *2018 IEEE/ACM Third International Conference on Internet-of-Things Design and Implementation (IoTDI*. IEEE, 2018.

[10] Md Tamzeed Islam, *Bashima Islam*, and Shahriar Nirjon. Soundsifter: Mitigating Overhearing of Continuous Listening Devices. In *Proceedings of the 15th Annual International Conference on Mobile Systems, Applications, and Services*. 2017.

[11] Md Mahbubur Rahman, Mohsin Yusuf Ahmed, Tousif Ahmed, *Bashima Islam*, Viswam Nathan, Korosh Vatanparvar, Ebrahim Nemati, Daniel McCaffrey, Jilong Kuang, and Jun Alex Gao. 'BreathEasy: Assessing Respiratory Diseases Using Mobile Multimodal Sensors.' *ACM International Conference on Multimodal Interaction (ICMI '20)*. ACM. 2020.

[12] Tousif Ahmed, Mohsin Yusuf Ahmed, Md Mahbubur Rahman, Ebrahim Nemati, *Bashima Islam*, Korosh Vatanparvar, Viswam Nathan, Daniel McCaffrey, Jilong Kuang, and Jun Alex Gao. Automated Time Synchronization of Multimodal Cough Events from Mobile Devices. *ACM International Conference on Multimodal Interaction (ICMI '20)*. ACM. 2020.

[13] Ravi Srinivasan, Md Tamzeed Islam, *Bashima Islam*, Zeyu Wang, Tamim Sookoor, Omprakash Gnawali, and Shahriar Nirjon. Preventive Maintenance of Centralized HVAC Systems: Use of Acoustic Sensors, Feature Extraction, and Unsupervised Learning. In *Proceedings of the 15th IBPSA Conference*. 2017.

[14] Jasper de Winkel, Carlo Delle Donne, Kasim Sinan Yildirim, Przemysław Pawełczak, and Josiah Hester. 2020. Reliable Timekeeping for Intermittent Computing. In Proceedings of the Twenty-Fifth International Conference on Architectural Support for Programming Languages and Operating Systems. 53–67.

[15] Josiah Hester, Nicole Tobias, Amir Rahmati, Lanny Sitanayah, Daniel Holcomb, Kevin Fu, Wayne P Burleson, and Jacob Sorber. 2016. Persistent clocks for batteryless sensing devices. ACM Transactions on Embedded Computing Systems (TECS). 2016.

[16] Amir Rahmati, Mastooreh Salajegheh, Dan Holcomb, Jacob Sorber, Wayne P Burleson, and Kevin Fu. TARDIS: Time and Remanence Decay in SRAM to Implement Secure Protocols on Embedded Devices without Clocks. In Proceedings of the 21st USENIX Conference on Security symposium. USENIX Association. 2012.

[17] Josiah Hester, Kevin Storer, and Jacob Sorber. Timely Execution on Intermittently Powered Batteryless Sensors. In Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems. ACM, 2017.

[18]https://www.niddk.nih.gov/health-information/professionals/diabetes-discoveries-practice/clinical-targets-for-continuous-glucose-monitoring-data

[19] https://www.verdict.co.uk/continuous-health-monitoring-wearables/

[20] https://learn.arm.com/route-to-trillion-devices.html

[21] https://www.iottechexpo.com/2018/11/iot/overcoming-iots-battery-barrier-with-self-powered-sensors/

[22] https://www.who.int/gard/publications/The_Global_Impact_of_Respiratory_Disease.pdf

[23] https://www.ibm.com/blogs/internet-of-things/protecting-endangered-rhinos/