RESEARCH STATEMENT

Abusayeed Saifullah

My areas of interest and expertise include Internet of Things (IoT), Real-Time and Embedded Systems, Wireless Networks, and Cyber-Physical Systems (CPS). My research addresses the grand challenges pertaining to timeliness, energy-efficiency, reliability, scalability, and performance optimization in these areas considering applications in autonomous and connected systems, industrial process control, smart city, smart farming, smart manufacturing, data center management, and wide-area monitoring through novel theory and system design.

1 Low-Power Wide-Area Network (LPWAN) for IoT

**LPWAN Design.** My significant research contributions include the design of an LPWAN architecture over the TV white spaces called SNOW (Sensor Network Over White spaces) [6, 7]. As an emerging IoT technology, LPWAN enables low-power (milliwatts) wireless devices to transmit at low data rates (kbps) over long distances (miles). Compared to its competitors like LoRa (Long Range) and SigFox that operate in the ISM band, and NB-IoT and 5G that mostly operate in the licensed band, SNOW avoids the crowd in the limited ISM band and the cost of licensed band and infrastructure. A key design goal of SNOW is to achieve high scalability by exploiting wide spectrum of the TV white spaces (free TV channels). Hence, I have designed its physical layer based on a novel Distributed implementation of OFDM (orthogonal frequency division multiplexing) for multi-user access, called D-OFDM. D-OFDM splits a wide spectrum into numerous narrowband orthogonal subcarriers enabling parallel data streams to/from numerous distributed nodes from/to a gateway connected to the cloud. It enables multiple receptions using a single antenna and also enables different data transmissions to different nodes using a single antenna, and does not need to rely on time synchronization. Thus it allows the nodes to transmit at low power (e.g., 0 to 20dBm) asynchronously to the gateway, enabling massive concurrent communications between numerous low-power IoT devices and the gateway over long distances (several miles). I have implemented SNOW on USRP (Universal Software Radio Peripheral) devices and also on several cheap IoT devices including TI CC1310 (as SNOW nodes) and made it open-source [7, 24–26]. The initial design received Best Paper Award nomination in ACM SenSys '16 [5]. Compared to the ISM band, white spaces offer less crowded spectrum, boasting an abundance in rural and suburbs. SNOW will hence be an ideal fit for many scalable and wide-area IoT applications such as smart farming, rural sensing, and oil/gas field management. It has the potential to be a leading LPWAN technology for IoT. SNOW has received much attention from industries and we are planning to commercialize it soon.

**Long-Lived LoRa.** LoRa is a popular LPWAN technology in the ISM band for wide-area IoT applications. Due to severe energy constraints of LPWAN devices, prolonging the network lifetime is a major consideration in IoT deployments. I have recently proposed Long-Lived LoRa, a link-layer protocol for LoRa, in which I have shown that lifetime can be maximized by consuming more energy in cases (which is counter-intuitive) [20]. By exploiting the LoRa’s capability of adjusting multiple transmission parameters, this approach enables low-cost packet offloading by battery-depleting nodes instead of high-cost direct forwarding. I have implemented the protocol on LoRa devices and evaluated its effectiveness through experiments.

**Embedded Learning Agent.** The rapid growth of LPWANs in the limited spectrum for various wide-area IoT applications brings forth the challenge of their coexistence. Today, LPWANs are not equipped to handle this impending challenge. It is difficult to employ sophisticated media access control protocol for low-power nodes. To improve the performance of a LoRa network under
coexistence with many independent networks, I have designed the first embedded learning agent based on a lightweight reinforcement learning (RL) at LoRa nodes [19]. This is done by developing a Q-learning framework while ensuring minimal memory and computation overhead at LoRa nodes. Testbed experiments show that the proposed Q-learning approach achieves an improvement of up to 39% in packet reception rate at the gateway while consuming up to 50% less energy compared to the traditional LoRa. Currently, I am also working on achieving both energy-efficiency and battery longevity in LoRa networks by incorporating reinforced learning into software defined batteries.

Real-Time LoRa. Today, industrial Internet of Things (IIoT) are emerging in large-scale and wide-area applications (e.g., oil-field management). Traditional wireless solutions for industrial automation depend on short-range wireless technologies (WireessHART, ISA100.11a), posing a big challenge to support the scale of today’s IIoT. To address this limitation, I have proposed to adopt LoRa for industrial automation. The fundamental building blocks of any industrial automation system are feedback control loops that largely rely on real-time communication. LoRa adopts a simple protocol based on ALOHA with no collision avoidance to minimize energy consumption which is less suitable for real-time communication. Existing real-time protocols for short-range technologies cannot be applied to a LoRa network due to its asymmetry between downlink and the uplink spectrum, predefined modes (class) of operation, and concurrent reception through orthogonal spreading factors. I have proposed RTPL- a Real-Time communication Protocol for LoRa networks. RTPL is a low-overhead and conflict-free communication protocol allowing autonomous real-time communication of low-energy devices and exploits LoRa’s capability of parallel communication [18]. Testbed experiments show that RTPL achieves on average 75% improvement in real-time performance without sacrificing throughput or energy compared to traditional LoRa.

2 Real-Time Wireless Sensor-Actuator Network in Industrial CPS

A wireless control system employs feedback control loops between sensors and actuators through a wireless mesh network. Industrial control applications make critical demands for reliable and real-time communication between sensors and actuators in order to avoid plant shutdowns or accidents. However, industry settings pose an unreliable environment for wireless communication making it difficult to meet these requirements. Industrial wireless standards such as WirelessHART mitigate frequent transmission failures through multi-channel communication and graph routing where a packet is transmitted through multiple paths and multiple channels. These networks hence require the development of a new real-time scheduling theory. In addition, the performance of a wireless control system induces a complicated problem involving multiple interrelated objectives (e.g., reliability, real-time performance, control performance) and decision variables (e.g., transmission schedule, routes, sampling rates). Hence, holistic optimization of control performance requires scheduling-control co-design that needs expertise from diverse disciplines.

Real-Time Wireless Scheduling. I have established a class of novel real-time wireless scheduling theories by bridging multi-channel wireless mesh networking and real-time scheduling domain [4,11–13]. I have provided a set of analyses to find communication delay bounds between the sensors and actuators. For wireless control with firm requirements on network latency, a delay analysis is required to quickly assess the schedulability of real-time flows, specially for admission control and workload adjustment in response to network dynamics. Recently, I have also proposed DistributedHART, a distributed real-time scheduling system for WirelessHART networks for scalable industrial process control [22]. The results have been implemented and evaluated on a physical testbed of my lab at Wayne State University.

Scheduling-Control Co-Design. Due to limited bandwidth in a wireless control network shared by many control loops, it is critical to co-design scheduling and control to optimize the control
Research Statement

Abusayeed Saifullah

Performance. I addressed the scheduling-control co-design problem of sampling rate selection of a wireless control system [10]. The resulting constrained optimization problem is challenging due to its non-differentiability and non-convexity. I have solved it through a convex relaxation as a promising approach for wireless-control co-design by integrating wireless networking, real-time scheduling, control, and optimization theory.

My work has provided the first set of results on real-time multi-channel industrial wireless networks, and represents a breakthrough in wireless control that has emerged as an exemplary class of industrial CPS. One paper was nominated for the Best Paper Award at RTAS '12 [10]. Another paper received the Best Paper Award at IEEE ICII '18 [23]. The results of DistributedHART can help in the future modifications to the WirelessHART standard.

3 Wireless Networked CPS for Data Center Power Capping

Through collaboration with Microsoft Research (Jie Liu, Ranveer Chandra, Bodhi Priyantha), I developed CapNet, a real-time wireless sensor network system for data center power capping [8,9]. In oversubscribing data centers, the peak power consumption of a cluster of servers above its cap has a specified time limit, called a trip time, depending on the magnitude of oversubscription. Power capping is the mechanism to bring the aggregate power consumption back to the cap within the trip time to prevent circuit breaker tripping. I designed CapNet based on IEEE 802.15.4, and implemented it for TinyOS platform. CapNet employs a distributed event-driven protocol that reduces the communication load significantly by triggering data collection only upon the detection of a potential event. It provides the first proof of concept design for using low cost wireless for data center power capping. Today’s data center management is typically designed in parallel to the production data network with a combination of Ethernet and serial connections with redundancy which does not scale well in terms of cost. As opposed to such wired management, CapNet can reduce the cost by 90%. My CapNet paper received the Best Paper Award at RTSS '14.

4 Real-Time Parallel Scheduling for CPS

Many complex CPS such as autonomous vehicle consist of a myriad of real-time tasks such as motion planning, sensor fusion, computer vision, and decision making algorithms that exhibit intra-task parallelism. For example, the decision making subsystem processes massive amounts of data from various sensors, where the processing on different types of sensors can run in parallel. Multi-core processors can enable these computation-intensive CPS having stringent timing constraints that cannot be met on single-core machines. Most classic results in real-time scheduling concentrate on sequential tasks on multiple cores. While they allow many tasks to execute simultaneously on a multi-core, they do not allow an individual task to run any faster on it than on a single-core.

Parallel Scheduling and Analysis. I developed various real-time parallel scheduling algorithms and theories for exploiting intra-task parallelism of parallel tasks, each represented by a directed acyclic graph (DAG), on multi-core [1, 3, 14, 21]. In a DAG, each vertex represents a thread of execution while the edges represent dependencies between vertices. DAGs represent tasks generated by most parallel languages (e.g., OpenMP, CilkPlus) and libraries, and are the most general model of deterministic parallel tasks. My key results include constant approximation ratios (in terms of processor speed-up bound) of scheduling performance of the proposed parallel algorithms.

Mixed-Criticality Multicore System. I have addressed parallel real-time scheduling for mixed-criticality (MC) CPS [16]. In an MC system, different criticality components are engineered to different levels of assurance (e.g., safety-critical, non-critical), with high criticality ones being the most costly to design and verify. For example, in avionics, engine and flight controls are safety-critical, but navigation and communication are not. In an emergency, safety-critical components must run
correctly while, in normal condition, all components need to run correctly. The key challenge in MC scheduling on CPU is that a task has different execution times for different criticality levels, of which a scheduling algorithm has no a priori knowledge. This hinders the conventional real-time scheduling theory to satisfactorily address MC scheduling. Unlike sequential tasks, MC scheduling of parallel tasks has seen only little progress to date. I have derived scheduling performance and analysis in terms of constant speed-up bound of my MC parallel scheduling.

**Incorporating Cache Benefit.** I have also addressed inter-thread cache benefits on multicore platform by incorporating instruction cache sharing into parallel scheduling [28]. For hard-real time systems, cache memory increases execution time variability, increasing the complexity of timing analysis. Cache-aware co-located scheduling aims to improve schedulability by carefully scheduling threads to share cached values. Cache sharing between threads potentially reduces task execution times and increases schedulability with fewer resources. Antithetically, co-located scheduling may reduce parallelism, decreasing efficiency. Thus, identifying the optimal set of threads to co-locate that minimizes the resources required while ensuring timing constraints is a complex challenge. I established optimal co-location as NP-Hard in the strong sense and proposed approximation methods for the co-located scheduling of parallel tasks [27]. An experimental RISC-V evaluation running on a QEMU platform confirms the benefits of the proposed methods.

My first work in real-time parallel computing is regarded as one of the pioneering efforts in this domain and received the Best Student Paper Award at RTSS ’11 [1]. It inspired much follow-up research and was cited 420+ times. The MC parallel scheduling work also received the Best Student Paper Award at RTSS ’19 [16].

5 Energy-Efficiency in Real-Time CPS

Both energy-efficiency and real-time performance are critical requirements in many embedded systems such as self-driving car, advanced robotic system, and disaster response. A recent study using the Ford Fusion autonomy system has revealed that 41% energy is consumed by the computing platform of a self-driving car. I have addressed real-time scheduling of parallel tasks, each represented by a DAG, while minimizing their CPU energy consumption on various multicore embedded systems [2, 14, 17]. Energy-aware real-time scheduling is challenging due to complicated relation between frequency, energy consumption, and execution. Existing study considered only sequential tasks. Energy-aware real-time parallel scheduling of DAGs is highly challenging due to the dependencies among the vertices as well as among their execution lengths. My contributions include the first energy-aware parallel scheduling of DAGs. It incorporates an adaptive frequency optimization engine through DVFS (dynamic voltage and frequency scaling) for minimizing CPU energy consumption into the classical real-time scheduling policies and makes them energy-aware. I have implemented the results on ODROID multicore boards [2, 17] and demonstrated up to 68% energy-saving compared to classical (energy-unaware) policies [2]. I have also recently implemented our energy-efficient policies on the Intel Xeon multiprocessor platform [15]. While I have considered only CPU energy, the results provide a strong fundamental basis to incorporate the other key components (e.g., GPU, system bus, and memory/cache) of energy consumption in the future work.
Selected Papers Cited in this Statement:


