RESEARCH PROJECTS

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A few of my research projects are as follows.

SNOW: An LPWAN Architecture for Wide-Area IoT and CPS

Today, WSNs face significant scalability challenges due to the requirements of emerging wide-area wireless monitoring and control applications (e.g., smart farming and smart cities) where thousands of sensors connect over long distances. Existing WSN technologies operating in the 2.4GHz spectrum (e.g., IEEE 802.15.4) facilitate such connections by forming multi-hop mesh networks, complicating the protocol design and network deployment. To address these limitations, I designed and developed *SNOW (Sensor Network Over White Spaces)*, a novel LPWAN technology by exploiting the TV white spaces (unused TV channels) [1, 2, 3]. SNOW achieves scalability and energy efficiency by enabling concurrent packets reception (Rx) at a base station (BS) using a single radio (Rx-radio) from numerous sensors and concurrent packets transmission (Tx) to numerous sensors from the BS using a single radio (Tx-radio), simultaneously. The Rx-radio and Tx-radio at the BS use the same set of TV channels split into narrowband subcarriers, i.e., subchannels optimized for scalability, energy efficiency, and communication reliability. Every sensor transmits/receives a spectral component of a *Distributed Orthogonal Frequency-Division Multiplexing (D-OFDM)* symbol asynchronously using an assigned subcarrier to encode/decode its packets. The BS uses a *Fast Fourier Transformation (FFT)/Inverse-FFT* to decode (using Rx-radio)/encode (using Tx-radio) different data from/to different sensors, which can scale to thousands of nodes at the same complexity over several kilometers. I also demonstrated the feasibility of SNOW by implementing it on a prototype hardware. The related papers are published at **ACM SenSys '16**, a premier single-track conference on embedded networked sensor systems with a **Best Paper Award Nomination** [1], ACM SenSys '17 [2], **IEEE/ACM Transactions on Networking** in 2018 that earned me the **Michael E. Conrad Outstanding Publication Award** from the Department of Computer Science at Wayne State University [3], and **IEEE ICESS '22** with the **Best Paper Award** [4].

Enhanced Scalability and Extended Coverage by Integrating Multiple SNOWs

As the LPWANs are evolving rapidly, they still face limitations in meeting the scalability and coverage demand of very wide-area IoT/CPS deployments (e.g., 74x8km^2 East Texas oilfield monitoring with tens of thousands of sensors [5, 6, 7]), especially in the infrastructure-limited rural areas. To enable this, I proposed a network architecture called *SNOW-tree* through seamless integration of multiple SNOWs where they form a tree structure and are under the same management/control at the tree root. Such integration, however, requires simultaneous intra- and inter-SNOW communications while avoiding the scalability-limiting inter-SNOW interference. I addressed this by formulating a constrained optimization problem whose objective is to maximize scalability by managing the spectrum sharing across the SNOWs, where each pair of neighboring BSs (i.e., SNOWs) communicate using a distinct special subcarrier. By proving the NP-hardness nature of the problem, I then proposed two polynomial-time methods to solve it: a greedy heuristic algorithm and a 1/2-approximation algorithm. I demonstrated the feasibility of this work by deploying 15 SNOWs, covering (25x15)km^2. Experimentation confirmed that both algorithms are highly effective in practice, the approximation algorithm providing a performance bound as well. This *seminal work in LPWAN integration* is published at **IEEE/ACM IoTDI '18**, a premier conference for the IoT research [5]. An extended version is published at **IEEE/ACM Trans. on Networking** [6].

A Practical Implementation and Deployment of SNOW

The SNOW implementation in [1, 2, 3] used the costly and large form-factored USRP (universal software radio peripheral) devices as LPWAN nodes, which limits its availability in practical deployments. To address this, I implemented SNOW using the low-cost and small form-factored commercial off-the-shelf

(COTS) devices. The COTS devices, however, face a variety of practical challenges that are very difficult to handle with their cheap radios. (1) The D-OFDM-based SNOW physical (PHY) layer degrades the reliability in the nodes by introducing severe inter-(sub)carrier interference (ICI) due to the signal power asymmetries in different subcarriers. (2) Due to the bandwidth asymmetries in the BS and nodes, subcarrier noise estimation is extremely difficult, thereby degrading the reliability and communication range. (3) Due to radio imperfections (e.g., frequency mismatch) in the BS and nodes, the orthogonality of the D-OFDM subcarriers breaks, introducing severe ICI and degrading reliability at the BS and nodes. Through this implementation, I addressed the above challenges in SNOW. Specifically, I handled the subcarrier power asymmetries by lowering their peak-to-average power ratio (PAPR). I also proposed a preamble-based (known sequence of bits) subcarrier noise estimation technique for the asymmetric subcarrier bandwidths. Additionally, I proposed a preamble-based subcarrier frequency offset estimation technique to handle the radio imperfections. Through this implementation, I also addressed the *classic* near-far power problem for wide-area SNOW deployment by formulating a predictive control-based adaptive transmission power mechanism at the nodes. I demonstrated COTS SNOW implementation on the TI CC1310 and CC1350 devices, reducing the cost and form-factor of a SNOW node by 30x and 10x, respectively, compared to the USRP-based SNOW implementation. This work is published at **IEEE/ACM IoTDI '19**, demonstrating high reliability, low-latency, and high energy-efficiency at the nodes [8]. An extended version of this work is published at **ACM Trans. on Embedded Computing Systems** [9].

A Tamper-proof and Transparent Framework for Event Ordering in the IoT Platforms

Today, the IoT platforms, including Samsung SmartThings, lack techniques for tamper-proof and transparent event ordering due to their device heterogeneity and device-centric logging mechanism. As a result, audit, diagnosis, and forensics of the causal relationships between the events in a trigger-action-based event chain become increasingly laborious and untrustworthy. Looking at a list of high-level device logs from an Iris platform: *"motion was detected by Iris outdoor camera at 11:13* AM*", "front door was unlocked at 11:13* AM*", "porch light was turned on at 11:14* AM*"*, it is not apparent why the porch light was turned on at 11:14AM. To answer that, I proposed a framework called *T-IoT (Transparent-IoT)* that enables automated tamper-proof transparency, ordering of events, and *knowledge representation* of the achieved order in the existing IoT platforms. I designed the T-IoT core by tailoring the blockchain protocol for the resource-constrained (e.g., limited storage and computational power/energy budget) IoT devices. The events are added as transactions in the blockchain ledger in their global order. The miners store a *partial consistent cut* of the ledger while the gateway stores the entire ledger. The miners replace their blocks as needed with the help of gateway, thus handling the storage requirement. To generate a new block, a miner has to solve a *modular arithmetic*-based puzzle using *Fermat's Little Theorem*, which is computationally lightweight but difficult for the IoT nodes to falsify. To achieve the global ordering of the events, I proposed a *vector clock*-based event ordering protocol customized for T-IoT. I also proposed a *backtracking-based* knowledge representation protocol where the gateway creates a provenance graph of the achieved order. To the best of my knowledge, *this is the first blockchain protocol that involves the resource-constrained IoT devices as block miners*. I implemented the T-IoT framework using an IoT gateway and 30 COTS IoT devices to demonstrate its feasibility. This work is published at **IEEE Internet of Things Journal** [10].

Boosting Reliability and Energy-Efficiency in Indoor LoRa

LoRa is a promising communication technology for enabling the next-generation indoor IoT applications. Very few studies, however, have analyzed its performance indoors, compared to the volume of outdoor studies. Besides, these indoor studies investigate mostly the RSSI (received signal strength indicator) and SNR (signal-to-noise ratio) of the received packets at the gateway, which, as we show, may not unfold the poor performance of LoRa and its MAC (medium access control) protocol – LoRaWAN – indoors in terms of reliability and energy-efficiency. In this project, we evaluated the performance of LoRaWAN and use its key insights to boost the reliability and energy-efficiency in indoor environments by proposing LoRaIN (LoRa Indoor Network), a new link-layer protocol that can be effectively used for indoor deployments. The approach to boosting the reliability and energy-efficiency in LoRaIN is underpinned by enabling constructive interference with specific timing requirements for different pairs of channel bandwidth and spreading factor and relaying precious acknowledgments to the LoRa nodes with the assistance of several booster nodes. The booster nodes do not need any special capability and can be a subset of the LoRa nodes. To our knowledge, LoRaIN is the first protocol for boosting reliability and energy-efficiency in indoor LoRa networks. We have evaluated its performance in an indoor testbed consisting of one LoRaWAN gateway and 20 LoRaWAN end-devices. Our extensive evaluation shows that when 15% of the end-devices operate as booster nodes, the reliability at the gateway increases from 62% to 95%, and the LoRa nodes are approximately 2.5x energy-efficient. This work has been accepted at **ACM/IEEE IoTDI '23** [11].

Coexistence of LoRa Through Embedded Reinforcement Learning

The rapid growth of LPWAN technologies in the limited spectrum 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. Coexistence handling for WiFi or traditional short-range wireless network will not work for LPWANs. Due to long range, their nodes can be subject to an unprecedented number of hidden nodes, requiring highly energy-efficient techniques to handle such coexistence. In this project, we address the coexistence problem for LoRa, a leading LPWAN technology. To improve the performance of a LoRa network under coexistence with many independent networks, we propose the design of a novel embedded learning agent based on a lightweight reinforcement learning at LoRa nodes. This is done by developing a Q-learning framework while ensuring minimal memory and computation overhead at LoRa nodes. The framework exploits transmission acknowledgments as feedback from the network based on what a node makes transmission decisions. To our knowledge, this is the first Q-learning approach for handling coexistence of low-power wide-area networks. Considering various coexistence scenarios of a LoRa network, we evaluated our approach through experiments indoors and outdoors. The outdoor results show that our Q-learning approach on average achieves an improvement of 46% in packet reception rate while reducing energy consumption by 66% in a LoRa network. In indoor experiments, we have observed some coexistence scenarios where a current LoRa network loses all the packets while our approach enables 99% packet reception rate with up to 90% improvement in energy consumption. This work has been accepted recently at **ACM/IEEE IoTDI '23**, a premier conference for the IoT research [12].

Collision Resolution in Wireless Communication

Interference between concurrent transmissions causes severe performance degradation in the IEEE 802.15.4-based networks, which emerges either due to the designated traffic pattern (e.g., many-to-one in convergecast) or hidden terminal problems. To address this, my advisor and I devised a method called *Reverse & Replace Decoding (RnR)* to decode all the collided packets from a single collision, as long as there exist collision offsets. In RnR, we take advantage of the unused channel capacity of the IEEE 802.15.4-based network deployments. We augment a packet by replacing its error-correcting bits with the bits in the reverse order they appear in the original packet, thus doubling the size. When two packets collide, we find the collision-free bits and replace them in the proper places of the packets by subtracting them from the collisions. This process progresses iteratively. I also extended the 2-packet collision decoding into m-packet ($m > 2$) collision decoding by transforming it to a system of linear equations, where each chunk is a variable and each chunk-level collision yields an equation. I implemented RnR on top of the IEEE 802.15.4 PHY layer, demonstrating its feasibility. RnR decoding is published at **IEEE SECON '17** [13], showing its low latency and energy efficiency.

Other Works

I have been involved in several other research projects towards mixed-criticality industrial wireless sensor-actuator networks (published in a workshop at **ICDCN '23** with the **Best Paper Award** [14]), integrating multiple SNOWs while minimizing the maximum network latency (published at **IEEE RTAS '21** [15]), prolonging the lifetime of LoRa networks (published at **IEEE ICNP '20** [16]), and schedulability analysis in wireless control systems (published at **IEEE ICII '18** with the **Best Paper Award** [17]).

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