1 Research Summary

My research[1] interests center around performance management, online failure detection, isolation and recovery in smart and connected cyber-physical systems, with a focus on transportation networks and smart grid. As such, I conduct research across distributed middleware, AI methods, component-based design methods, anomaly detection and system level assurance for these systems. Model integrated computing methods are crucial for my work as they provide a way to describe the architecture of the system formally and enable generation of a variety of artifacts: analytical models to conduct timing, reliability, security, performance, etc. analysis from a single source. A summary of my research activities to date is as follows.

- **Key Contributions**: Key contributions of my work include the development and deployment of resilient decision support systems for Metropolitan Transit Authority in Nashville, design and deployment of energy analysis and optimization framework for Chattanooga Regional Transit Authority, robust incident prediction and dispatch system developed for Nashville Fire Department and a privacy-preserving decentralized system for peer-to-peer energy exchange. Other contributions include middleware for online fault-detection and recovery in software intensive distributed systems and a robust software model for building cyber-physical applications, along with spatial and temporal separation among different system components which guarantees fault isolation.
- **Publications**: I have published 150 papers. 88 of them were written as an Assistant Prof (citations (>1850), h-index (22) and i10-index (46)[2].). Out of these 28 (17 in TT position) are journal publications, including top journals such as ACM Transactions on Cyber-physical systems, Elsivier Journal of Systems and Software and Embedded System Letters. 9 (6 in TT position) are book chapters. 52 (37 in TT position) are highly selective refereed conference publications (acceptance rates less than 40 %) such as International Conference on Autonomous Agents and Multiagent Systems (typical acceptance rate <25%), International Conference of Cyber-Physical Systems (ICCPS) (typical acceptance rate <30%) and SMARTCOMP (typical acceptance rate <30%). 34 (12 in TT position) papers appeared in selective refereed conference publications such as Prognostics and Health Management Conferences. There are 31 workshop papers (20 in TT position).
- **Invited talks**: As an Assistant Professor I have given 23 invited presentations (not including paper presentations) at various conferences, NSF workshops, universities and industry.
- **Software Products**: The software products I have developed have been actively used by the research community. Notable software products include (a) an ARINC-653 emulator for Linux and (b) first open source operating system implementation for FACE standard (partially developed in TT position), (c) Modular platform for Smart Grid applications (developed in TT position), (d) CHARIOT toolsuite for extensible cyber-physical systems

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[1] This research is carried out through my *Smart Computing Over Physical Environments* (SCOPE) group (`http://scope-lab.org`). The lab has been funded in part by grants from NSF, NASA, DOE, ARPA-E. AFRL, DARPA, Siemens, Cisco and IBM.

[2] `https://scholar.google.com/citations?user=5J3w9OoAAAAJ&hl=en`

(partially developed in TT position), (e) TRANSAX - a middleware for transactive energy systems and (f) MODICUM - a decentralized edge computing solution.

- **Patents**: I have been granted one provisional patent for Method and System for Secure and Private Forward Trading Platform in Transactive Microgrids. There are two submitted and pending patents: (1) Method and System for Data-Driven Forecasting of Cascading Effects in Networked Systems and (2) Decentralized Method and System for Real Time Anomaly Detection In Transportation Networks.
- **Research Grants**: Total grant support in the PI position as an assistant professor is 3.4 million dollars. Total grant support as a Co-PI as an assistant professor is approximately 30.9 million dollars. My cumulative grant support throughout my career as a researcher is over 45 million dollars. I have received these grants from NSF, DARPA, DOE, DOD, ARPA-E, ARL, Siemens, IBM , CISCO, NASA and AFOSR.
- **Professional Research Service**: I have served 11 times as a chair or co-chair for international conferences during my career. In addition I have served over 20 times as a program committee member. Over the years, I have also frequently reviewed grants for NSF, NASA and DOE.
- **Research in Practice**: My research work in the public transit and emergency response area has been adopted by Nashville departments and Chattanooga departments and has been frequently cited in the press[3]. The CHARIOT, ARINC-653 Component Model and RIAPS toolsuites have been transitioned to open source community.

2 Summary of Research Areas and Contributions

My research in cyber-physical systems and smart connected communities focuses on the full stack of the architecture. Studying the full stack is useful because resilience and safety depends upon the interactions between the layers and to fully optimize and implement the innovations we need to able to solve problems across the layers. As such I have conducted research in *middleware*, *performance management*, *blockchains*, *system resilience* and *assured autonomy*. This full stack approach has allowed me to make a number of contributions in four application areas: *Public Transportation Systems*, *Emergency Response Systems*, *Smart Grids* and *transactive energy systems*. I summarize the key contributions in these areas, dividing them in to research horizontals and research verticals.

2.1 Research Horizontals

The table below summarizes the research contributions and publications for cross cutting research concerns.

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[3] `https://www.ft.com/content/140ae3f0-1b6f-11ea-81f0-0c253907d3e0`

Area	Research Contributions	Publications
Blockchain and CPS	• Mechanisms to implement privacy and analyze safety tradeoff. • Mechanisms to verify the correctness of smart contract logic. • Mechanisms for testing integration of blockchains in CPS at scale. • Mechanisms for efficient market implementation using hybrid solver pattern.	**After TT:** [Las+19; WSD19; Zha+19a; Mav+19; Eis+19a; Las+18; Eis+18; LMD18; Las+17; Wal+17]
Middleware for CPS	• Modular and composable application frameworks for avionics, satellites and smart grid. • Device abstractions for safely isolating applications. • Support for runtime monitoring, fault diagnosis and mitigation. • Integrated tools for hierarchical scheduling analysis across temporal partitions. • Domain-specific modeling languages for reduction of accidental complexity. • Middleware for managing smart grid applications. • Reusable transactive market framework for microgrids. • Middleware for managing transportation applications.	**After TT:** [Tal+20; She+20; Dub+19b; DG19; She+19a; Gho+19; She+19b; KDK19; PSD19; Tal+19; Dub+19a; GDB18; Pra+18; Du+18c; Eis+17c; Kha+17; Eis+17b; Völ+17; Dub+17; Pra+16a; Emf+16; PDG16b; Dub+16; PDG16a; Pra+16] **Before TT:** [Bal+15; Pra+15b; Pra+15a; Lev+14; Kar+14; Bal+14b; Bal+14a; Pra+14; Pra+14a; Mar+14; ODK14; Pra+14b; Ott+13; Dub+13b; Shi+13; Emf+13; Dab+12; Dub+12; Cha+12; DKM12; DKM11b; Dub+10; Bal+10]

Performance Management	• Predictive performance management and optimal resource allocation for cloud systems using queuing theoretic methods. • Dynamic bayesian network based performance assessment of cyber-physical systems under uncertainty.	**After TT:** [She+20; Pet+20; She+19b; Kha+17; NDM17; Nan+17; PDG16b; Nan+16b] **Before TT:** [Emf+14; KDK14; Mar+14; Mah+13a; MDK12; Meh+12b; DMK12a; Meh+12a; Mon+12; RDG11; MDK11; Roy+11; Abd+11; Meh+11; DKM11a; Meh+11; Meh+10; Bal+10; PDP10; Pic+10; Dub+09a; Dub+09c; DKA09]
Assured Autonomy	• Mechanisms for identifying out of distribution input data for resource constrained devices. • Mechanisms for automating assurance case generation. • Hardware testbed for evaluating assured autonomy algorithms. • Dynamic simplex weighted strategies for smoothing the transition to the simplex controller.	**After TT:** [Ram+20a; Ram+20b; Ram+20c; Sun+20; Har+19b; Har+19c; Bur+19; Ram+19; Har+19a]

Resilience and Reliability for CPS	• Heuristics and semantic mapping for solving dynamic reconfiguration problem within satisfiability modulo theories framework. • Reliability driven autonomic system reconfiguration methodology. • Fault detection and diagnosis in hard real-Time software assemblies using automatically inferred fault propagation graphs. • Fault diagnosis in mitigation controllers using Timed Causal Diagrams (TCD) and its application to transmission lines. • Fault detection and diagnosis in transportation networks.	**After TT:** [Has+20; BDL19; BSD19; Wil+19; Bas+19a; Pra+18; Sun+18a; NMD18; NDM18; Chh+18a; Chh+18b; Chh+17b; DKP17; Chh+17a; Pra+16b; Mar+16; PDG16a; Nan+16b; Nan+16a; Bis+16a; Bis+16b] **Before TT:** [Mah+15; Pra+15b; Chh+15a; Mah+14; Pra+14a; Nan+14; DK13; Mah+13b; Pra+13; DKM13; Mah+13a; MDK12; Dab+12; Qia+12; DMK12a; DMK12b; Nor+11; MDK11; Abd+11; DKM11a; Sax+10; Dub09; Dub+09b; DMK09; Dub+08a; Dub+08b; Nor+07; Nor+06; Dub+06; Kes+06; Dub+05]

2.2 Research Verticals

The table below summarizes the research contributions and key publications for cross three application areas in which my research group has made progress.

Area	Research Contributions	Publications
Smart Grid	• Fault diagnosis in mitigation controllers using Timed Causal Diagrams (TCD) and its application to transmission lines. • Studying the criticality of power system networks using TCD. • Machine learning algorithms for data-driven anomaly detection and event-classification • Mechanisms for power systems defense against dynamic cyber-attacks.	**After TT:**[Has+20; Chh+20; Dub+19b; Tu+19; Has+18; Tu+18a; Du+18a; Tu+18b; Du+18b; Du+18c; Chh+18a; Chh+18b; Chh+17b; Chh+17a; Has+17; Has+17b; Du+17; Has+17a; Chh+16; Dub+16] **Before TT:**[Mah+15; Jai+15; Chh+15b; Mah+14; Dub+13a]
Transactive Energy	• Method and system for secure and private forward trading platform in transactive microgrids • Framework for studying IoT based transactive systems with Gridlab-D and Opal RT • Study of privacy and safety tradeoffs for transactive energy systems • Development of a resusable middleware framework for transactive energy systems • Study of security problems in blockchain based transactive energy systems.	**After TT:** [Las+19; Zha+19b; Eis+19b; Eis+19a; Las+18; Eis+18; Eis+17a; Las+17; Ber+17; Kva+17; NED16]

Smart Transportation	• Context-sensitive analysis and prediction of long-term, short-term and real-time delays in sparse public transit networks. • Algorithms for optimizing the seasonal schedule of public transit considering seasonal delays. • Modular trip planner and social routing policies for multimodal transportation options. • Method and system for data-driven analysis and forecasting of cascading effects of congestion. • Decentralized method and system for real time anomaly detection In transportation networks. • Mechanisms for analyzing and predicting the energy costs for public transit. • Mechanisms for optimizing the assignment of vehicles to trips to optimize the energy costs. • Data-driven simulator for analyzing the transportation demand management policies in urban environments. • Low-resolution camera based traffic density and pedestrian density estimation.	**After TT:** [Tal+20; Bar+20; BDL19; Sun+19; Bas+19b; ND19; PSD19; Tal+19; Wil+19; SDR19; Bas+19a; Oru+19; Bar+18; Sun+18b; SDR18; Sam+18; SDW17; Gha+17; SSD17; Sun+17; Oru+16; She+16; Sun+16] **Before TT:**[Dub+15]
Smart Emergency Response	• Mechanisms for analyzing the factors affecting incidents on road networks and highways. • Robust prediction of likelihood of accidents in a large metropolitan area using online survival analysis and long short term memory networks. • Algorithms for optimizing the dispatch strategies using the incident prediction models. • Development of an uncertain concept graph (UCG) to model the uncertainty in knowledge of state in dispatch operations.	**After TT:**[Pet+20; Muk+19; Pet+19; Pur+18; Muk+17; Pet+17]

3 Research Contribution Narrative

In this section I provide the detailed narrative of my research contributions and approach.

3.1 Research Horizontals

- **Blockchains for CPS:** The emergence of Bitcoin and Blockchain technology has sparked interest in CPS because it provides solutions to the challenges of multi-stakeholder CPS by providing participants the capability to not only exchange data and services in a decentralized and perhaps anonymous manner, but also the capability to preserve an immutable and auditable record of all transactions in the system. Such transactive platforms are actively being suggested for use in Healthcare, Smart Energy Systems, and Smart Transportation Systems. These platforms can provide support for privacy-preserving and anonymizing techniques, such as differential privacy, fully homomorphic encryption, and mixing. Furthermore, the immutable nature of records and event chronology in these platforms supports high rigor and auditability. The decentralized nature of these platforms ensures that any adversary needs to compromise a large number of node to take control of the system.

  Blockchains form a key component of these platforms because they enable participants to reach a consensus on any state variable in the system without relying on a trusted third party or trusting each other. Distributed consensus not only solves the trust issue, but also provides fault-tolerance since consensus is always reached on the correct state as long as the number of faulty nodes is below a threshold. Further, blockchains enable performing computation in a distributed and trustworthy manner in the form of smart contracts. However, while the distributed integrity of a blockchain ledger presents unique opportunities, it also introduces new assurance challenges that must be addressed before protocols and implementations can live up to their potential. For instance, smart contracts deployed in practice are riddled with bugs and security vulnerabilities. A recent automated analysis of 19,336 smart contracts deployed in practice found that 8,333 of them suffered from at least one security issue. Further, there are challenges such as computational efficiency and physical device integration.

  Along with the collaborators my research group has developed a number of novel techniques to solve these challenges including the hybrid solver pattern [Las+18; Eis+18; LMD18], scalable testing of IoT applications with blockchains [WSD19; Wal+17], ability to verify the smart contract code [Las+19; Mav+19] and integrate it with the devices using Resilient Information Architecture Platform for Smart Grid (RIAPS) middleware [Las+18; Las+17; Eis+19b; Eis+17b; Eis+17a; Ber+17]. A recent research challenge that we have been investigating in this area is the problem of information obfuscation – especially the tradeoff between keeping persistent open information about the CPS operations (required for safety and auditability) and hiding the information mechanisms such as mixing protocols.

- **Middleware for CPS**: Middleware is required for both operations as well as compositional analysis of cyber-physical systems such as smart grid and transportation networks. My approach for this has been to use component-based design. Component-based software engineering (CBSE) has been accepted as a standard practice to develop robust, modular and maintainable software stacks for networked embedded systems. The guiding principles of CBSE are interfaces with well defined execution models, compositional semantics and analysis. In my research I extend this notion to develop a robust software foundation for distributed cyber-physical systems, including transportation and power networks. My work in this area has made several contributions, including ARINC-653 Component Model (ACM) [DKM11b], which combines the principle of spatial and temporal partitioning with the interaction patterns derived from the CORBA Component Model (CCM). The main extension over the the CCM are as follows: (a) The synchronous (call-return) and asynchronous (publish-subscribe) interfaces can be equipped with monitors that validate pre- and post-conditions over data that is passed on the respective interface, (b) The relevant portions of the state of the component can also be observed via a dedicated state interface, enabling the monitoring of invariants, (c) The resource usage of the component can be monitored via a resource interface that component uses for allocating and releasing resources and (d) The timing of component execution can be observed via control interface such that instance execution time violations can be detected. Given these extensions, component-level monitoring can be accomplished that evaluates pre- and post-conditions on method invocations, verifies the state invariants, tracks the resource usage, and monitors the timing behavior of the component.

My work on DREMS (Distributed Real-Time Embedded Managed Systems) component model [Dub+17; Bal+15; Lev+14; Kar+14; Emf+13; Dub+12] extended ACM to networked cyber-physical systems that can be used by several concurrent users by allowing configurable real-time scheduling policies in addition to configurable secure information flow policies. Both of these component models followed a single threaded execution model for components, which helped avoid synchronization primitives that often lead to non-analyzable code and can cause run-time deadlocks and race conditions. Furthermore, along with my collaborators, I have developed resilient deployment and configuration techniques for managing these applications [PDG16a; Bal+14a; Pra+14; Pra+14a; ODK14; Pra+14b; Dub+13b; Dab+12]. One of the key innovations in DREMS was development of fine-grained privileges for controlling access to system services. As part of this effort we developed a novel Multi-Level Security (MLS) information sharing policy across distributed architectures [Lev+14; ODK14; Dub+13b; Dub+12].

- **Performance Management and Modeling:** Building on the foundation of the component-based middleware enables us to also explore the problem of component placement both in response to performance concerns as well as failures. In my research, I have developed methods to create models that assist in performance prediction and capacity planning for these components [She+20; Emf+14; KDK14; Mar+14; Meh+12b; RDG11; Roy+11; Meh+11; Meh+11; Meh+10; Dub+09a; Dub+09c; DKA09]. An integral part of this work is the ability to deploy sensors without affecting the performance of the rest of the system. For that I developed a novel feedback control based for scheduling the sensors [DKA09]. Further, we had to develop mechanisms that can adapt system and manage performance even under degraded scenarios. For this, we developed approaches based on runtime adaption while ensuring that the other partitions or applications in the system are not affected [Dub+19a; Dub+17; Dab+12; Bal+10]. Few recent works looked into the affect on of sensor uncertainty on the performance models [NDM18; NDM17; Nan+16b; Nan+16a; Nan+14].

- **Fault Detection and Isolation in Distributed CPS**: Identifying faults in these systems in distributed CPS like power networks and transportation networks is difficult because with naive statistical methods there is a high-likelihood that we find secondary or tertiary affects and are not able to isolate the true cause of failure, which in some cases might be unobservable. For example, there are studies by North Electric Reliability Corporation (NERC) which states that relay or automatic control misoperations can account for nearly all major system events. Effect of failures in protection system components, protection settings, software tools, and human decisions impacting power system physical components are not captured either. In the absence of a system-wide integrated fault model, faults are identified by directly observing the associated anomaly or a set of anomalies as part of a pattern. However, this technique fails when a large number of alarms occur within a short time period. It has been noted that in the case of transmission systems this leads to a situation where the utility operators are quickly overwhelmed with alarms.

  Another problem in these systems is the large geographical area over which the system is spread. That implies the analysis has to consider the likelihood that the data itself is corrupt or that the controllers responsible for maintaining safety in an area, such as the protection relays and road side units in transportation network are themselves faulty. Current research gap is in developing efficient models and tools for performing fault diagnostics and predicting the progression of failure cascades. The key enabler to solving this problem is the introduction of components such as PMUs (power networks) and high resolution cameras (transportation networks) that provide local snapshots of the system state to a central control authority. While these new sources provide richer data sets, fusing all the data available is still a challenge.

  Our approach to solving this challenge is to use a mix of data-driven and model-based techniques. First we use statistical neighborhood measures to identify the areas affected by the discrepancy and develop a hypothesis if the failure is indeed a physical anomaly. Then we use a discrete event model that captures the causal and temporal relationships between failure modes (causes) and discrepancies (effects) in a system, thereby modeling the failure cascades while taking into account propagation constraints imposed by operating modes, protection elements, and timing delays. This formalism is called Temporal Causal Diagram (TCD) and can model the effects of faults and protection mechanisms as well as incorporate fine-grain, physics-based diagnostics into an integrated, system-level diagnostics scheme. The uniqueness of the approach is that it does not involve complex real-time computations involving high-fidelity models, but performs reasoning using efficient graph algorithms based on the observation of various anomalies in the system. TCD is based on prior work on Timed Failure Propagation Graphs (TFPG). When fine-grain results are needed and computing resources and time are available, the diagnostic hypotheses can be refined with the help of the physics-based diagnostics. Finally, we use both data-driven approach like LSTM and graphical neural networks and the TCD models to prognosticate the effect of failures.

- **Software Health Management:** Software is one of the leading causes of failures in cyber-physical systems. Therefore, we need to extend the fault detection and isolation methods I described earlier to software intensive systems. This is possible if the software is constructed using well-defined components with formally described interfaces and semantics (provided by my work on the middleware described above), then the behavior and/or failure propagation across the software assembly can be deduced. Together with my collaborators, I have created a design and runtime environment to show how we can generate a Timed Failure Propagation Graph (TFPG) from software assemblies and then use it in runtime to isolate faulty components. This is possible because the data and behavioral dependencies (and hence the fault propagation) across the assembly of software components can be deduced from the well-defined and restricted set of interaction patterns supported by the framework. We also showed that fault containment techniques could be used to provide the primary protection from propagating failures into the high-criticality components and overall protect the system health management framework as well. These techniques were demonstrated on the ADIRU models of Boeing 777 [Mah+13b; DKM13; MDK12; Dab+12; DMK12a; DKM12; DMK12b; MDK11; DKM11a]. Most notably, we recreated a past malfunction that led to severe in-flight turbulence and showed how our technique could help in such situations.

- **System Resilience**: I have focused extensively on developing mechanisms to recover from component-failures [DKP17; Pra+18] by either reinstalling the components automatically or recovering the system functionality with alternative compositions in case of device and hardware failures [Pra+16b]. The key idea is to encode and use the design space of the cyber-physical system. This design space presents the state of an entire platform. It includes information about different resources available, well known faults, system goals, objectives and corresponding functionalities that help achieve different system goals, components that provide aforementioned functionalities, and possible different ways in which these components can be deployed and configured (this is captured using a domain specific language) [Pra+15b; Pra+15a; Pra+14a; Pra+14b]. The design space can expand or shrink depending on addition or removal of related entities. A configuration point represents a valid configuration which includes information about a specific deployment scenario given a set of component instances and physical nodes on which these component instances can be deployed. A change in the state of a platform is represented by transition from one configuration point to another in the same design space. An initial configuration point represents the initial state, whereas the current configuration point represents the current state of a platform. Configuration points and their transition are critical for the self-reconfiguration mechanism that I have developed. The key idea is to reconfigure by migrating/transitioning from a faulty configuration point to a new configuration point by solving the problem using efficient SMT solvers. Additionally, if we have past information about component failures, we can reconfigure components to maximize the likelihood that the mission will succeed [Nan+16a; Nan+14].

- **Assured Autonomy**: The motivation for this horizontal research area is resilience. In recent years, AI based components are being heavily used in CPS, including in my research. Despite their impressive capability, using them in safety critical applications is challenging because: (1) they learn from training data, and subtle changes in the images during testing could cause these components to predict erroneously, (2) testing and verifying these components is complex and sometimes not possible, and (3) safety and assurance case development of systems using these components is complicated. I have been focusing on methods to identify anomalies and recover from failures as well as develop system level safety assurance arguments. Till now, we have developed a methodology to use a class of variational autoencoder call β-VAE in combination with dissimilarity metrics like Kullback–Leibler divergence to perform anomaly detection on the input data streams [Ram+20c; Sun+20]. Once an anomaly is detected we use a weighted simplex strategy to transition to a safe controller. Instead of using only a single control output (as in Simplex Architecture), we designed a weighted ensemble of the two control outputs. The weights are computed dynamically to improve the balance of safety versus performance of the system [Ram+20a; Ram+19]. Finally, we have developed a methodology to semi-automate the generation of assurance cases for CPS with AI components [Ram+20b]. We have also built a test-bed called Deep NN-Car for experimentation and validation of these approaches [Bur+19].

- **Improving Computational Processing at Edge:** Developing an edge cloud is one of the big concerns for cyber-physical systems because latency to the cloud is a big issue. Under DOE and ARPA-E funding we have been developing a middleware that can support edge cloud called RIAPS. It is built upon a lot of our prior work in the area of componentized software frameworks for real-time systems and provides solutions for security, fault isolation, fault recovery, device abstractions, time synchronization and correct-by construction design. Recently, we have extended this work to create a computational outsourcing market called MODICUM for edge systems. It is a decentralized system for outsourcing computation. MODICUM deters participants from misbehaving, which is a key problem in decentralized systems, by resolving disputes via dedicated mediators and by imposing enforceable fines. However, unlike other decentralized outsourcing solutions, MODICUM minimizes computational overhead since it does not require global trust in mediation results. We provide analytical results proving that MODICUM can deter misbehavior, and we evaluate the overhead of MODICUM using experimental results based on an implementation of our platform.

3.2 Research Verticals

The cross-cutting concerns mentioned in the previous section have allowed me to develop innovative applications in both transportation as well as Power Networks. I study these two application domains because they both have an inherent network relationship that affects the fault progression and cascade. I discuss these innovations below.

- **Transactive Energy Systems:** Transactive energy systems have emerged as a transformative solution for the problems faced by distribution system operators due to an increase in the use of distributed energy resources and rapid growth in renewable energy generation. They are tightly coupled cyber and physical systems, which require resilient and robust financial markets where transactions can be submitted and cleared, while ensuring that erroneous or malicious transactions cannot destabilize the grid. In the last five years, we have used this research vertical to drive our research in the area of resilient decentralized CPS. As such we have developed a novel decentralized platform called TRANSAX (provisionally patented) [Las+19; Zha+19b; Eis+19b; Eis+19a; Las+18; Eis+18; LMD18; Eis+17a; Las+17; Ber+17; Wal+17; Kva+17; NED16]. It enables participants to trade in an energy futures market, which improves efficiency by finding feasible matches for energy trades, reducing the load on the distribution system operator. It provides privacy to participants by anonymizing their trading activity using a distributed mixing service, while also enforcing constraints that limit trading activity based on safety requirements, such as keeping power flow below line capacity. One of the key innovations in TRANSAX was the development of a novel hybrid solver concept, combining the trustworthiness of distributed ledgers with the efficiency of conventional computational platforms. This hybrid architecture ensures the integrity of data and computational results—as long as majority of the ledger nodes are secure—while allowing the complex computation to be performed by a set of redundant and efficient solvers.

- **Smart Grid:** Resilience in connected cyber-physical systems such as electrical power systems is of paramount importance for the socio-economic welfare of the society. These systems are designed to be resilient, for example, power systems are designed to be one failure tolerant and need to be protected as shown by our analysis in [Has+20; Has+18; Has+17b]. However, multiple failure, specifically cascaded failures do occur and result in systemic damage. Traditional approach is to use high-fidelity physics model to study the failure in these systems. However, these models fail to scale to large networks, especially when several multiple contingencies occur as a result of both physical failures and cyber failures. In my research, I have co-developed a novel graphical modeling formalism called temporal causal diagrams that can efficiently model fault progression paths in connected cyber-physical systems, even in systems with the built-in automatic fault-protection mechanisms like protection relays [Chh+18a; Chh+18b; Chh+17b; Chh+17a; Chh+16; Jai+15; Chh+15b]. Traditional model-based analyses find it hard to analyze such fault protection modes because of the complexity of mode switches. Recently, we have started the work of augmenting temporal causal diagram with data-driven monitors, which further reduces the runtime complexity of the online observers. Lastly, we have been developing middleware [Dub+19b; Gho+19; Völ+17; Eis+17b] that enables development and deployment of robust decentralized smart grid applications [Tu+19; Tu+18a; Du+18a; Tu+18b; Du+18b; Du+18c; Du+17; Jai+15].

- **Smart Transportation** This research vertical addresses the problem of urban transportation and congestion by building analytical tools that help the customers and the transit agencies reduce uncertainties and optimize the transit operations. We adress this problem at three fronts - Data Analytics, Planning and analysis tool for understanding and projecting the impact of transportation choices, and developing scalable data stores that can enable cities to operate their own data lakes and analytics engines.

- **Data Analytics** We focus on data analytics to understand bottlenecks and improve the operational reliability. For this, we start by first collecting multimodal data about transit operations, traffic, public events and congestion from cities of Nashville and Chattanooga. Then, we perform data analytics to understand the causes of transit delays and help provide tools that inform the community as well as transit operators how to manage both long term planning as well as short term delays.
- **Understanding Delays and Optimizing Schedule**: The on-time arrival performance of buses at stops is a critical metric for both riders and city planners to evaluate the reliability of a transit system. Identifying the bottlenecks in transit networks that often have abnormal delay is the first step for scheduling optimization. We built a prescriptive analytics mechanism to identify historical bus delay patterns and locate the bottlenecks in the transit network by measuring transit performance. Further, to identify and isolate the cause of temporary disruptions: such as accidents, sports games, adverse weather we built a neural network based classifier. To project the delay affects in future due to short term events we built multi-task deep neural networks that utilize contextual features (e.g., scheduled sports games and forecasted weather conditions) to make context-aware predictions of the expected travel delay, as well as the likelihood of accidents on the bus routes.
- **Simulation Frameworks** As part of the work to improve the efficiency of public transit and urban transportation in general, we also build solutions that will educate the community on benefits of public transit. The resulting simulation framework evaluates the effect of personal transportation choices and also helps cities evaluate the impact of incentive policies in nudging commuters towards alternate modes of travel, such as bike and car-share options. We leveraged MATSim, an agent-based simulation framework, to integrate agent preference models that capture the altruistic behavior of an agent in addition to their disutility proportional to the travel time and cost. These models are learned in a data-driven approach and can be used to evaluate the sensitivity of an agent to system-level disutility and monetary incentives given, e.g., by the transportation authority. This framework provides a standardized environment to evaluate the effectiveness of any particular incentive policy of a city, in nudging its residents towards alternate modes of transportation. We show the effectiveness of the approach and provide analysis using a case study from the Metropolitan Nashville area.
- **Energy Prediction Framework**: One of the key challenges is to improve the overall energy efficiency of the transit operations. For this purpose, we are developing real-time data sets containing information about engine telemetry, including engine speed, GPS position, fuel usage and state of charge (electrical vehicles) from all vehicles in addition to traffic congestion, current events in the city and

the braking and acceleration patterns. These high-dimensional datasets allow us to train accurate data-driven predictors using deep neural networks such as energy consumption given various routes and schedules. We can then use these predictors for the energy optimization of its fleet of vehicles.

- **Smart Emergency Response:** The objective of this research is to understand and improve the resource coordination and dispatch mechanisms used by first responders. The problem of dispatching emergency responders to service accidents, fire, distress calls and crimes plagues urban areas across the globe. In prior art, as well as practice, incident forecasting and response are typically siloed by category and department, reducing effectiveness of prediction and precluding efficient coordination of resources. Further, most of these approaches are offline and fail to capture the dynamically changing environments under which critical emergency response occurs, and therefore, fail to be implemented in practice. Consider the classical problem of emergency response. The goal of responders is to minimize the variance in the operational delay between the time incidents are reported to when responders arrive on the scene.

  Solving this problem requires not just sending the nearest emergency responder, but sometimes proactively placing emergency vehicles in regions with higher incident likelihood. Sending the nearest available responder by euclidean distance ignores road networks and their congestion, as well as where the resources are stationed. Greedily assigning resources to incidents can lead to resources being pulled away from their stations, increasing response times if an incident occurs in the future in the area where responder should be positioned. Now, consider solving this problem when there is a high uncertainty in the veracity of the request due to either communication failures or due to the nature of the communication medium – in extreme disruptions the most common communication mechanism used is social media, however, the social media requests have a lot of uncertainty in terms of duplication, spatial location etc. Ultimately, the methods developed in this work can be applied to other domains where multi-resource spatio-temporal scheduling is a challenge. Through funding from the National Science Foundation, my team has been investigating five sub-problems in this area.

  - **Incident Prediction Using Online Survival Analysis and Long Short Term Memory Networks** - We have developed a novel online approach to incident prediction that predicts incidents in time and space. Previous work in this domain has treated this as a batch learning problem in which incident prediction models are learned once, and are subsequently used to aid response decisions. This fails to capture the changing dynamics of urban systems in which emergency responders operate, and we bridge this gap by creating an online incident prediction algorithm. Our framework includes an online survival model for incident prediction and a recurrent neural network model for learning environmental features affecting dispatch.
  - **Uncertainty Quantification by Uncertain Concept Graphs (UCG)** We have been developing the theory of uncertain concept graphs that combine graphical fault propagation models with dynamic Bayesian networks. The UCG is

capable of representing dynamic knowledge of a disaster event from heterogeneous data sources, particularly for the regions of interest, and resources/services required. The information sources, incident regions, and resources (e.g., ambulances) are represented as nodes in UCG, while the edges represent the weighted relationships between these nodes. We have developed a theoretical solution for probabilistic edge inference between nodes in UCG. The output of such structured summarization over time can be valuable for modeling event dynamics for the decision support in the real world beyond emergency management, across different smart city operations such as transportation.

- **Dispatch Suggestion Framework** - We formulate the problem of dispatching responders to incidents as a Semi Markov Decision Process (SMDP). However, solving this class of problems online is extremely slow and fails to work in dynamic environments since any change in the problem definition (the number of responders, or the position of a depot) renders the learned policy stale. In order to tackle this problem, we use an important observation - one need not find an optimal action for each state as part of the solution approach since at any point in time, only one decision-making state might arise that requires an optimal action. This difference is crucial, as it lets us bypass the need to learn an optimal policy for the entire MDP. Instead, we describe a principled approach that evaluates different actions at a given state, and selects the one that is sufficiently close to the optimal action. We do this using sparse sampling, which creates a sub-MDP around the neighborhood of the given state and then searches that neighborhood for an action. In order to actualize this, we use Monte-Carlo Tree Search (MCTS).
- **Policy Framework For Evaluation of Decisions** - We have been developing a framework for testing the dispatch algorithms and then enable reasoning over anomalous decisions. Specifically, to incorporate the future environment in dispatch decisions, a discrete event simulator is used. It consists of a grid-based model of the environment, including where EMS/Fire stations are located. For each grid cell, there is a learned incident prediction model (using survival analysis) that is used to sample future likely incidents. Responders and their states are represented by agents that move around the grid from stations to incidents, and a traffic model and router are used to simulate travel times between grids. When an incident occurs and a dispatching decision must be made, the following steps occur. First, future incidents are sampled from the spatio-temporal prediction models. Then, each agent builds a Monte Carlo Search Tree to estimate the utility of each of its potential actions. Future incidents are used as future states, and the actions of other agents are approximated.
- **Resilient Distributed Middleware** - The online decision framework we have built is only as good as the communication framework and the computation framework on which it can run. In extreme circumstances the whole city can be cut off from the cloud providers and might not be in a position to run the online framework. To support partitioned execution capability we have been developing a decentralized middleware that is capable of recovering from communication network partitions and distributed computations tasks across available edge compu-

tation resources. The key to resilience in this framework is the use of a distributed ledger to maintain data consistency and use marked based mechanisms to offload tasks to computation resources. A smart contract in the system is responsible for implementing the task placement correctly.

4 Graduate Students

Till now I have graduated three students as listed below.

1. **Chinmaya Samal, CS (2019)**. Time-dependent and Privacy- Preserving Decentralized Routing using Federated Learning (MS Thesis, Vanderbilt University).
2. **Fangzhou Sun, CS (2018)** - co-advised with Jules White, 2018. Algorithms for Context-Sensitive Prediction, Optimization and Anomaly Detection in Urban Mobility (Doctoral dissertation, Vanderbilt University).
3. **Pradhan, Subhav, CS (2017)**, co-advised with Aniruddha Gokhale. Algorithms and Techniques for Managing Extensibility in Cyber-Physical Systems (Doctoral dissertation, Vanderbilt University).

The students who I advise are listed below

1. **Geoffrey Pettet, CS**: He is working on the emergency response vertical and develop the coordination algorithms
2. **Michael Wilbur, CS**: He works in the performance management area and develops energy prediction and optimization algorithms for smart transit systems.
3. **Nithin Guruswamy, CS**: He works in the system resilience area and is developing AI based fault diagnosis methods for edge cloud systems.
4. **Sanchita Basak, EE**: She works in the fault diagnostics area and is responsible for fault management in our smart transit and smart grid vertical
5. **Scott Eisele, EE**: He is responsible for improving system resilience using Blockchains and works on the transactive energy and edge cloud veriticals.
6. **Shreyas Ramakrishnan, EE**: Shreyas's research interests are in system assurance area. He is developing the weighted simplex strategy and anomaly detection methods for neural networks.
7. **Matthew Burruss, CS** (Dual BS/MS): Matthew is researching methods to improve the robustness of neural network classifiers and his research is aligned with the assurance horizontal.

5 Research Collaborators

My main research collaborators are following.

1. Dr. Aron Laszka - Assistant Professor, Electrical Engineering and Computer Science Department, University of Houston.
2. Dr. Lillian Ratliff - Assistant Professor, Electrical and Computer Engineering Dept., Washington State University.

3. Dr. Hemant Purohit - Assistant Professor, Information Sciences & Technology Department, George Mason University
4. Dr. Yevgeniy Vorobeychik - Associate Professor, Computer Science and Engineering, Washington University in St. Louis
5. Dr. Sajal Das - Professor at the Computer Science department at Missouri University of Science and Technology
6. Dr. Sherif Abdelwahed - Assistant Professor, Electrical and Computer Engineering Dept., Virginia Commonwealth University.
7. Dr. Hiba Baroud - Assistant Professor, Civil and Environmental Engineering, Vanderbilt University, Vanderbilt University.
8. Dr. Gautam Biswas - Professor, Electrical Engineering and Computer Science Department, Vanderbilt University.
9. Dr. Aniruddha Gokhale -Associate Professor, Electrical Engineering and Computer Science Department, Vanderbilt University.
10. Dr. Gabor Karsai - Professor, Electrical Engineering and Computer Science Department, Vanderbilt University.
11. Dr. Srdjan Lukic - Assistant Professor, School of Electrical and Computer Engineering, NCSU.
12. Dr. Douglas Schmidt - Professor, Electrical Engineering and Computer Science Department, Vanderbilt University.
13. Dr. Anurag Srivastava - Assistant Professor, School of Electrical Engineering and Computer Science, WSU.
14. Dr. Jules White - Associate Professor, Electrical Engineering and Computer Science Department, Vanderbilt University.

6 Research Impact

The impact of my research has been demonstrated in the following ways.

Publications, funding and service The primary impact of my work is demonstrated by more than 1800 citations with an h-index of 22 and over 45 million dollars in combined funding that I have received as PI and Co-PI over the years. The software that I have developed over the years have led to further research opportunities. For example, my work on ARINC-653 component model (ACM) [DKM11b], which combined the principle of spatial and temporal partitioning with the interaction patterns derived from the CORBA Component Model (CCM) eventually led to a DARPA grant. In that project we developed DREMS (Distributed Real-Time Embedded Managed Systems) component model [Bal+15; Lev+14], which extended ACM to networked cyber-physical systems that can be used by several concurrent users, by allowing configurable real-time scheduling policies in addition to configurable secure information flow policies.

Industrial Collaboration My research on performance management, resilience and platform design have led to collaborations with several companies including IBM Research, Siemens, and Cisco. The results from my research have been applied to diverse domains including avionics, smart grid, industrial systems, and transportation networks.

Community Engagement Since 2015 my research has been actively focused on smart and connected communities. As a result, the results from our projects have been deployed for Metro Transit Authority, Nashville Fire Department and Chattanooga Regional Transit Authority. I currently manage a sensor test bed in Gulch, which enables edge computing research with focus on managing faults in low-cost computers such as Raspberry-PI.

7 Future Research Direction: Challenges and opportunities presented by the rapid integration of mobility and electrical infrastructure

The transportation landscape is changing at a faster pace today than at any point in history. The three revolutions (electrification, autonomy, sharing) are causing the entire automotive industry and communities to rethink long-term strategies to manage the sea-change occurring on our roadways. What makes the problem worse is that this integration is unfolding spontaneously, without considerations of any centralized control or plans of inter-operability, which often results in unintended interactions leading to vulnerabilities in the cyber, physical as well as social domain. We may consider ride-sharing services as an example - while providing a new mode of transportation to many, widespread offerings of ridesharing may lead to increased congestion as shown from studies conducted in San Francisco and New York City. Newly proposed fleets of electrified autonomous taxis might lead to millions of zero-occupancy vehicle miles traveled (VMT) with negative environmental impact and have yet another unintended consequence, namely the increased dynamic load induced on the electric grid by the vehicles. Lack of system wide planning and protection can allow an adversary to use false data about electricity prices to lead the electrical robot taxis into a congested area or create heavy electrical load on specific substations. A precursor of the problems that might appear, has been shown by several pilots of electric scooters in many cities, necessitating new regulations to reduce the problems of illegal parking and unsafe use. It is clear that an integrated study of the impact of these multi-domain systems across the community is required, to be able to assess the traffic flow impact, social impact and power distribution impact. This integrated study guides my future research. As such I believe we need to investigates following areas.

- **Handling Big Data generated by the integrated Mobility and Electricity Infrastructure**: Each aspect of large-scale data collection, analysis and operation is a complicated piece of a puzzle, which are intricately connected to each other through multiple dependencies. Data collection involves large-scale instrumentation, be it to monitor traffic or power grid. Usually such instrumentation comes as sizeable monetary commitments for often cash-strapped communities who want to “future proof” their investment. Related questions such as data storage, communication (fiber-optic vs. 5g) are similarly important investment considerations. Visualization of large data brings its own set of challenges - a data pull from a large number of intersection cameras can quite easily overwhelm the available bandwidth of a network. Scalable algorithms that can actually process this large data for global optimization of a specific metric is as rich in opportunities as it is challenging due to processing, communication and implementation constraints.

- **Integrated co-simulation of city systems considering human behavior and urban planning** Large scale agent-based simulation platforms such as Sumo, Vissim and Matsim have always been and will continue to be crucial tools in planning for future trends, but now they will need to be interfaced with micro-scale modeling systems such as automated-driving toolboxes (Matlab), automotive simulation models (ASM) from DSpace for predicting behavior of self-driving cars and its interaction with static and dynamic traffic elements. These autonomous driving toolboxes in turn might need to interface with visualization and synthetic data generation platforms, such as Unreal Engine, IPG carmaker, Metamoto, Cognata, etc. In creating this "digital twin", the human factor also needs to be given due consideration. Further these physical simulation models will integrate these behavior models and incentive mechanisms within the co-simulation systems to analyze the impact of various strategies.
- **Resilient Decentralized Control** In theory this vast network of interacting cyber-physical systems can be controlled in a centralized manner. However, a centralized solution faces a number of challenges. First, it requires a central controller to gather all state information, sensor data, etc. Since network connections have limited bandwidth and the amount of data can be substantial, control decision may suffer significant delays. Second, a central controller constitutes a single-point-of-failure. While failover mechanisms may prevent the system from critical failures that cause shutdowns, they cannot provide the level of contiguous availability that is required for the stability. An alternative strategy is to focus on developing decentralized controllers for controlling the traffic flow and energy flow across the community. Such decentralized control can also make the system more resilient by distributing the security controls throughout the system. However, multi-agent control is challenging since it would entail creating, for each agent, an accurate model that includes knowledge of other agents' states and control actions that cover interactions with the other agents. Recently, we have applied these approaches for emergency response for example [Pet+20; Muk+19; Muk+17], but they often assume cooperative execution. In transportation context, agents might have their own selfish interests and will make the problem of decentralized control even harder.
- **Failures, Security Threats and Recovery** Disruptions, degradation, and attacks on the transportation and electrical grid network can severely hamper critical operations of cities and dramatically increase cost for managing them. The structure, interdependence, and fragility of these systems is hard to model. While response to perturbations has been quantified, recovery strategies for perturbed networks have usually been either discussed conceptually or through anecdotal case studies. An integrated network science-based data-driven models for measuring, comparing and interpreting responses to cyber-physical attacks as well as recovery strategies might be important. The methods can directly apply in domains where an adversary or failure might compromise a subset of sensors/actuators and is interested in steering the controlled process into some unsafe state. Furthermore, quantitative frameworks need to be generalizable across natural, engineered and human systems, offering an actionable approach for emergency management in particular and for

cyber physical network resilience in general.

- **Equity and Fairness** The quest for optimum in every aspect of planning and execution of a CPS-enabled city has raised some pressing ethical questions. Wide scale access to real time data and the opportunity to plan and actuate subsystems at a very high resolution has only helped to propel these issues to the forefront. Consider the dilemma that will need to be resolved as we will need to prioritize traffic flow for achieving system-optimal performance at the cost of enhanced travel times for selected commuters.

8 Related Publications

Journal Articles

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