Appendix A - Research Skills

The advent of interconnected smart and intelligent systems has enabled efficient delivery of different kinds of services in areas such as transportation, smart homes, smart grid, medical and healthcare, etc. Such a large conglomeration of connected devices/entities form the Internet of Things (IoT). The large scale integration of heterogenous entities in an IoT brings with it the inherent complexity of system level design and analysis. In addition, these IoT systems are comprised of a large number of real-time embedded systems, which require schedulability analysis and design techniques specific to real-time systems. My primary research interests address these challenges and fall under the broad theme of "**Scalable Design and Performance Analysis of IoT and Real-Time Embedded Systems**", especially delving into topics like *edge computing based services for intelligent transportation* and/or *safety critical real-time embedded computing systems for automotives.*

One of the major challenges in performance analysis of applications running in IoT and Real-Time Embedded (RTE) systems is the predictability of performance objectives. Predictability in RTE systems is influenced by the variability in available computation, communication and memory resources for processing an application as a result of contention on the resources from competing tasks. However, the RTE system is typically confined in space and dimension and its performance analysis is not influenced by network communication technology. On the other hand, the performance analysis of an IoT system needs to consider a larger system view involving network communication technology and possibly user input devices in addition to the RTE sub-systems. In this context of both systems mentioned above, I envision to work towards proposing novel robust and efficient design and analysis techniques for *timing predictability*, *energy/thermal efficiency*, *system resilience* and *optimal resource usage.*

1 Prior Work

1.1 Performance Analysis and Design of RTE Systems

During my PhD, I have developed several formal analysis techniques to perform worst/average-case analysis in various problem contexts pertaining to executing hard/soft real-time applications on multiprocessor system-on-chips (MPSoCs). The three techniques developed had its theoretical roots in Real-Time Calculus (RTC) (a well known tool for compositional analysis of distributed systems) and partly also in resource reservation-based scheduling [1, 3, 4]. Further, I have also developed analytical techniques based on Stochastic Network Calculus to derive quality-of-service (QoS) quantified as probabilistic bounds on performance for multimedia applications running on MPSoC platforms [7, 8]. In addition, I proposed techniques to perform fast hybrid simulation [5, 6] for performance analysis of multimedia MPSoC platforms.

As a PostDoctoral Researcher, I have worked on several problems delving into proposing new design techniques for better timing predictability of executing concurrent applications on MPSoC platforms. These works were based on the concepts of composability and hybrid design space exploration (DSE) of NoC-based multi-tile platforms using spatial isolation [9] and temporal isolation [10] of shared resources. One line of work also addressed the issue of contention on buses by firstly developing a method to reconfigure the AMBA AHB bus at runtime [11] and then proposing an online algorithm to perform reconfiguration of bus scheduling policy between non-preemptive fixed priority (NPFP) scheduling to time division multiple access (TDMA) scheduling with low complexity [12].

1.2 Analysis and Design of Edge Computing-based Intelligent Connected systems

Delivery of data/services to vehicles via the edge while the vehicle is on the move requires allocation of adequate amount of memory, computation and communication resources on the edge nodes. In my previous work [15], I formulated this data/service delivery problem as an optimization problem, which minimizes the system wide total bandwidth cost of the edge nodes. As a follow up work, I proposed a social welfare based optimization framework [16] for data/service delivery considering both delivery time and total edge bandwidth cost.

2 Future Research Plan

2.1 Performance Analysis and Design of RTE Systems

Under this theme, I will be working on problems in scheduling and analysis of RTE systems delving into aspects such as *data freshness*, *security over shared resources*, *mixed criticality* and *multimode system operation*, while ensuring timeliness, energy/thermal efficiency and resilience objectives. All these themes will be primarily explored in the context of RTE systems relevant to automotive industry. One of my recent papers [13] (won the **best paper award**), which was co-authored with a graduate student I mentored, proposed a method to determine the periods of tasks in chains of arbitrary length while satisfying end-to-end freshness constraints with only few assumptions regarding the scheduling algorithm used. I plan to continue this line of research by proposing a data freshness aware scheduling technique for energy/temperature minimization. I would also like to explore the effect of faults on data freshness and formulate conditions that will minimize the effect of faults on data freshness. Security-aware scheduling [14] is an interesting and important research direction, which has many unanswered problems. Within this direction, I would like to propose analysis and scheduling techniques considering dynamic priority scheduling strategies, which have not been considered yet. Further, my research will also span the dimension of analysis and scheduling strategies for mixed criticality multimode embedded systems, which is an area I am working on lately.

These works are currently being performed under the seed grant provided by IIIT Hyderabad.

2.2 Analysis and Design of Edge Computing-based Intelligent Connected systems

My team of 2 MS students have worked on three very important problems on efficient data/service delivery heuristic algorithms for connected vehicles via edge nodes when they are on the move. The first work proposed a fast heuristic which delivered data/service and was able to service a large number of vehicles very close to the optimal approach (which was published in IEEE Cloud 2018) with very less departure from edge bandwidth cost optimality and significant orders of improvement in the time required to deliver data/service. This paper was published in the Rank A IEEE Vehicular Technology Conference (VTC) 2021. The above work was further improved by proposing a novel approach to determine the overlap of vehicles within the coverage area of an edge node. The vehicle overlaps were not considered in the previous work and the assumption was that all the vehicles passing through an edge's coverage region does it during the same time, which is the worst-case assumption. This resulted in over allocation of edge resources to the vehicles resulting in servicing of lesser number of vehicles compared to the optimal approach. Our proposed method including estimation of vehicle overlaps enabled the service of more vehicles and improved the work submitted to IEEE VTC 2021. We are now working on a more enhanced version of the data/service delivery problem by including the delivery time along with the edge bandwidth cost resulting in a multi-objective function, which was formulated as a social welfare objective function. This problem is being solved using a game-based strategy and an approximation of the objective function.

In addition to data/service delivery for connected vehicles, one other area that I have started exploring is the use of deep learning (DL) algorithms for connected vehicle applications using the edge device. As DL based edge analytics is performed on resource constrained edge devices, I see the potential to conduct research on DL algorithms that use intelligent information generation and sharing mechanisms to optimize the energy efficiency and thermal requirements of the edge device. Currently, there is a lot of research on developing efficient DL algorithms to execute on the resource constrained edge devices. One direction in this research is to trade off accuracy of the DL inference by pruning some feature data and thereby reducing resource usage and time. We are exploring this in a research project looking at real-time efficient traffic flow prediction on Indian city roads using edge nodes. If there are safety critical automotive tasks that need to be executed on the edge device (for e.g., offloaded tasks from vehicles) along with the DL inference task, a pertinent problem will be to analyze how much accuracy of the DL task needs to be traded off with the timeliness of the safety critical tasks, in the worst-case, given an arrival pattern of the safety critical tasks. **Currently, all the above works are partly being conducted with a generous grant from the Department of Science and Technology (DST), India under the National Mission on Interdisciplinary CPS**.

Vehicle Platoon formation is another scenario where there is a lot of potential of using edge computing and deep learning algorithms. Most of the platoon formation decisions are performed either offline or with very limited local information. A very important challenge in forming efficient platoons is the dynamic nature of traffic making it very difficult to use the offline decisions. Therefore, data collected by edge nodes can be used to make intelligent decisions regarding the optimal platoon formations considering traffic flows and vehicle routes. The grand idea here is to develop algorithms and system to facilitate real-time efficient platoon formations for logistics companies.

Fault tolerant and security algorithms and supporting systems for commercial UAVs is a challenging problem due to the low cost of these UAVs and the limited resources. Currently, I am a Co-PI in 2 DST funded projects that delve into providing efficient fault tolerance and security techniques considering the limited resources on the UAV. There are several potential problems in this area as there is no prior work that has looked at developing a runtime system that will take care of making dynamic decisions regarding what fault tolerant control mechanism or security algorithm needs to be executed

when a fault or an attack is detected.
Safety is another important aspect in Intelligent Transportation, especially in vehicles. There is lot of work being carried out in improving the safety of four wheelers due to rising interest in self driving cars. However, there is still very little work in safety mechanisms for a two wheeler. Currently, we are working on developing efficient deep learning algorithms to detect accidents and bike driving events. These will be deployed on an edge device, which will detect accidents or driving events in real time. The grand idea of this project is to provide a 2 wheeler platform to collect driving data and also provide the platform for use by researchers. Additionally, we would like to develop a system which can assign drive quality index to the quantify the driving quality of a rider.

2.3 Development/Analysis of IoT Middleware Implementations in IIIT-H Smart City Living Lab

After joining IIIT-H, I joined the team of Smart City Living Lab project and took on the leadership role as the faculty responsible for the development of 8 software infrastructure to enable the usage of an IoT Middleware for inter- operability (based on a widely used oneM2M standard) of the different IoT applications/verticals. Currently, there is a team of 6-7 students working in this project. We are using an open source implementation of the oneM2M standard called OM2M. The initial challenges were to improve the performance of data storage and retrieval from the OM2M implementation. After achieving some improvement, we worked on the integration of the OM2M implementation with an external database Postgres. We have conducted some experimental research on the performance of the setup with varying request frequencies and number of requests on the real testbed of IIIT-H Living Lab. Currently, we are also integrating the OM2M-Postgres database setup with a data exchange framework called IUDX that will be used for Smart Cities in India. Towards this, we are working with a team in IISc who work on the IUDX framework. I have also worked on the development of IoT nodes that measure the TDS value of water in RO tanks and sump in the IIIT-H campus so as to keep track of the quality of water. As part of this work, we published a paper in the reputed conference IEEE WF-IoT 2021 which proposed a non invasive technique of measuring TDS values of water in RO tanks. The TDS sensor was also calibrated using machine learning.
To summarize, I have very active interest in design and analysis problems for systems consisting of connected entities in the area of Smart Cities, Smart Transportation, etc.

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