Form CoverPage
(Rev. 3/2014)
(RTI)

RESEARCH PROPOSAL
Submitted To
TEXAS DEPARTMENT OF TRANSPORTATION
By
The University of Texas at Austin
Center for Transportation Research
(PERFORMING AGENCY/S)

RFP #: **15-1**

Technical Area: 3

Document Date: August 28, 2014

Project Title: Communications and Radar-Supported Transportation Operations and Planning (CAR-STOP)

Length of proposal validity: 1 year

PART I. Brief Project Description.
The primary outcome from this project will be a framework to harness and mature wireless technology to improve transportation safety, with a focus on frontal collision warning/collision avoidance (CW/CA) systems. TxDOT traffic and safety experts will be asked for feedback and input throughout the course of the project, along with experts from the industry (such as our partner National Instruments), to ensure that the framework is consistent with real-world constraints and situations. At the same time, the close interactions among academics, industry leaders in roadway safety, and TxDOT will ensure that the framework is transformative.

The project will represent a multimodal and multidisciplinary effort focusing on research and technology transfer activities to promote the integration of cutting-edge developments in communications and radar technology with transportation systems to improve roadway safety (and thereby also the accessibility and reliability) of the travel experience of Texans. The project will be directed toward (a) improving the use of wireless technologies to obtain data from multiple and heterogeneous sources, (b) machine learning and data driven information extraction capabilities that are localized and timely, and (c) bringing information together with driver characteristics and behavior to develop safety systems that are effective and customized.

PART II. Proposed project start date and duration: 11/1/14-10/31/15
(12 months)

PART III. Project Budget. The total estimated project cost, which includes all authorized direct and indirect costs which may be incurred by the Performing Agency(s), is shown below along with a breakdown by fiscal year and agency. Attached hereto as Exhibit A and made a part of this agreement is an annual Itemized Budget for each Performing Agency which details proposed project costs for each fiscal year of this project.

Budget Breakdown
(Attach an itemized budget for each fiscal year

FY	Agency	Budget	FY	Agency	Budget
15	UT/CTR	$674,983			
16	UT/CTR	$102,017			

Total Project Budget: $777,000

PART IV. Project Supervision. The Performing Agency Research Supervisor, whose agency shall be the lead agency, and other primary research staff are named below.

	Name	Title	Agency	Phone No.	Email
Research Supervisor	Chandra Bhat	Professor	UT/CTR	512-471-4535	bhat@mail.utexas.edu
Researcher or PI	Robert Heath	Professor	UT/CTR	512-686-8225	rheath@utexas.edu
Researcher or PI	Joydeep Ghosh	Professor	UT/CTR	512-471-8980	jghosh@utexas.edu

Form ExhA
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Itemized Budget - Exhibit A

Project No: ______________________

Agency: UT/CTR

Fiscal Year: 2015
Indirect Rate: 10%

Revision Number: ______________
Revision Date: ______________

	Estimated Budget	Itemization		Total Costs
DIRECT COSTS				
Salaries & Wages (by category)		list each Professional individually	% of time*	
Professional (Combine all Professionals)	$ 164,345	Chandra Bhat	10	
		Robert Heath	10	
		Joydeep Ghosh	10	
		Visiting Professor, Nuria Gonzalez	30	
		PhD Researcher(s) (4)	200	
		MS Researcher(s) (4)	200	
Subprofessional & Technical	$ 161,000			
Clerical (Non-routine)	$ 12,892			
Total Salaries and Wages				$ 338,237
Fringe Benefits (provide details at the University's option)	$ 98,089			
Total Fringe Benefits				$ 98,089
Expendable Goods & Supplies (provide details at the University's option)				
	$ 4,079	Misc. Office Supplies		
	$ -			
	$ -			
	$ -			
Total Expendable Goods & Supplies				$ 4,079
Operating & Other Expenses				
Included in Modified Total Direct Costs				
In-State Travel	$ 4,165	Project Related Travel		
Out-of-State Travel	$ -			
Other	$ 1,666	Phone/internet		
	$ 3,332	Reproduction/Printing		
	$ 7,500	3 laptop computers at $2500 each		
	$ -			
	$ -			
	$ -			
Excluded from Modified Total Direct Costs **				
Tuition (in lieu of partial or total salary)	$ 72,208			
Other				
Total Operating & Other Expenses				$ 88,871
Subcontracts ** (list each subcontractor separately, with a brief description of the work)				
List name of individual consultant or name of company	$ -			
	$ -			
	$ -			
Total Subcontracts				$ -
Equipment (items $5,000 and over) ** (list each item separately)				
	$ 75,000	National Instruments hardware and software equipment		
(note: equipment is for use in WP 3.1.1.)	$ 25,000	Radar and communication modules		
	$ -			
	$ -			
	$ -			
Total Equipment				$ 100,000
TOTAL DIRECT COSTS				$ 629,276

INDIRECT COSTS		
54.5 (%) of Modified Total Direct Costs***	**MTDC ** =** $ 457,068	$ 249,103
less University's Contribution 44.5 (%)		$ (203,396)
TOTAL INDIRECT COSTS CHARGED TO PROJECT (limited to Indirect Rate stated at top of page)		$ 45,707
TOTAL PROJECT COST		$ 674,983

* Include estimated % charged time for each Professional during the period of this budget
** Calculate MTDC based on the University's negotiated (federal) F&A agreement. Per OMB Circular A-21, MTDC should never include equipment, tuition reimbursement, rental costs, scholarships and fellowships, and the portion of each subcontract over $25,000.
*** Enter University's federally approved indirect cost rate % in blank. Form will calculate total, based on MTDC.
Note: This electronic form contains formulas that may be corrupted when adding or deleting rows, or by conversion of the spreadsheet. The university is responsible for the accuracy of the budget submitted.

Itemized Budget - Exhibit A

Form ExhA
(Rev. 5/2013)
(RTI)

Texas Department of Transportation

Project No: ______________________________

Agency: UT/CTR

Fiscal Year: 2016
Indirect Rate: 10%

Revision Number: ______________
Revision Date: ______________

	Estimated Budget	Itemization	Total Costs
DIRECT COSTS			
Salaries & Wages (by category)		list each Professional individually % of time*	
Professional (Combine all Professionals)	$ 16,668	Chandra Bhat	
		Robert Heath	
		Joydeep Ghosh	
		PhD Researcher(s) (4) 200	
		MS Researcher(s) (4) 200	
Subprofessional & Technical	$ 32,200		
Clerical (Non-routine)	$ 7,487		
Total Salaries and Wages			$ 56,355
Fringe Benefits (provide details at the University's option)	$ 16,343		
Total Fringe Benefits			$ 16,343
Expendable Goods & Supplies (provide details at the University's option)			
	$ 818	Misc. Office Supplies	
	$ -		
	$ -		
	$ -		
Total Expendable Goods & Supplies			$ 818
Operating & Other Expenses			
Included in Modified Total Direct Costs			
In-State Travel	$ 835	Project Related Travel	
Out-of-State Travel	$ -		
Other	$ 334	Phone/internet	
	$ 668	Reproduction/Printing	
	$ -		
	$ -		
	$ -		
	$ -		
Excluded from Modified Total Direct Costs **			
Tuition (in lieu of partial or total salary)	$ 19,128		
Other			
Total Operating & Other Expenses			$ 20,965
Subcontracts ** (list each subcontractor separately, with a brief description of the work)			
List name of individual consultant or name of company	$ -		
	$ -		
	$ -		
Total Subcontracts			$ -
Equipment (items $5,000 and over) ** (list each item separately)			
	$ -		
	$ -		
	$ -		
	$ -		
	$ -		
Total Equipment			$ -
TOTAL DIRECT COSTS			$ 94,481

INDIRECT COSTS			
54.5 (%) of Modified Total Direct Costs***		**MTDC ** =** $ 75,353	$ 41,068
less University's Contribution 44.5 (%)			$ (33,532)
TOTAL INDIRECT COSTS CHARGED TO PROJECT (limited to Indirect Rate stated at top of page)			$ 7,536
TOTAL PROJECT COST			$ 102,017

* Include estimated % charged time for each Professional during the period of this budget
** Calculate MTDC based on the University's negotiated (federal) F&A agreement. Per OMB Circular A-21, MTDC should never include equipment, tuition reimbursement, rental costs, scholarships and fellowships, and the portion of each subcontract over $25,000.
*** Enter University's federally approved indirect cost rate % in blank. Form will calculate total, based on MTDC.
Note: **This electronic form contains formulas that may be corrupted when adding or deleting rows, or by conversion of the spreadsheet. The university is responsible for the accuracy of the budget submitted.**

15-1
Technical Area: 3

Communications and Radar-Supported Transportation Operations and Planning (CAR-STOP)

Project Abstract

The primary outcome from this project will be a framework to harness and mature wireless technology to improve transportation safety, with a focus on frontal collision warning/collision avoidance (CW/CA) systems. TxDOT traffic and safety experts will be asked for feedback and input throughout the course of the project, along with experts from the industry (such as our partner National Instruments), to ensure that the framework is consistent with real-world constraints and situations. At the same time, the close interactions among academics, industry leaders in roadway safety, and TxDOT will ensure that the framework is transformative.

The project will represent a multimodal and multidisciplinary effort focusing on research and technology transfer activities to promote the integration of cutting-edge developments in communications and radar technology with transportation systems to improve roadway safety (and thereby also the accessibility and reliability) of the travel experience of Texans. The project will be directed toward (a) improving the use of wireless technologies to obtain data from multiple and heterogeneous sources, (b) machine learning and data driven information extraction capabilities that are localized and timely, and (c) bringing information together with driver characteristics and behavior to develop safety systems that are effective and customized.

1. IMPLEMENTATION

Results from this project, labeled CAR-STOP (Communications and Radar-Supported Transportation Operations and Planning), will be implemented in several ways. Figure 1 illustrates the project idea and the objectives for the different phases. The primary outcome of this project will be a framework to harness and mature wireless technology to improve transportation safety, with a focus on frontal collision warning/collision avoidance (CW/CA) systems. TxDOT traffic and safety experts will be asked for feedback and input throughout the course of the project, along with experts from the industry (such as our partner National Instruments), to ensure that the framework is consistent with real-world constraints and situations. At the same time, the close interactions among academics, industry leaders in roadway safety, and TxDOT will ensure that the framework is transformative. The framework will be tested rigorously in Phases II and III (if allowed to proceed to these phases), with issues of prototype development, component functionality and integration investigated in Phase II, and specific field investigations conducted in Phase III to identify optimal implementation pathways of improvements to transportation safety. Phase I will itself demonstrate the concepts and technologies in a software test-bed scenario, and produce a full concept of operations (CONOPS) together with a complete and detailed inventory of the requirements for full deployment in an operational environment. Thus, the efficacy of the framework will be investigated, albeit in a controlled and limited environment, even in Phase I.

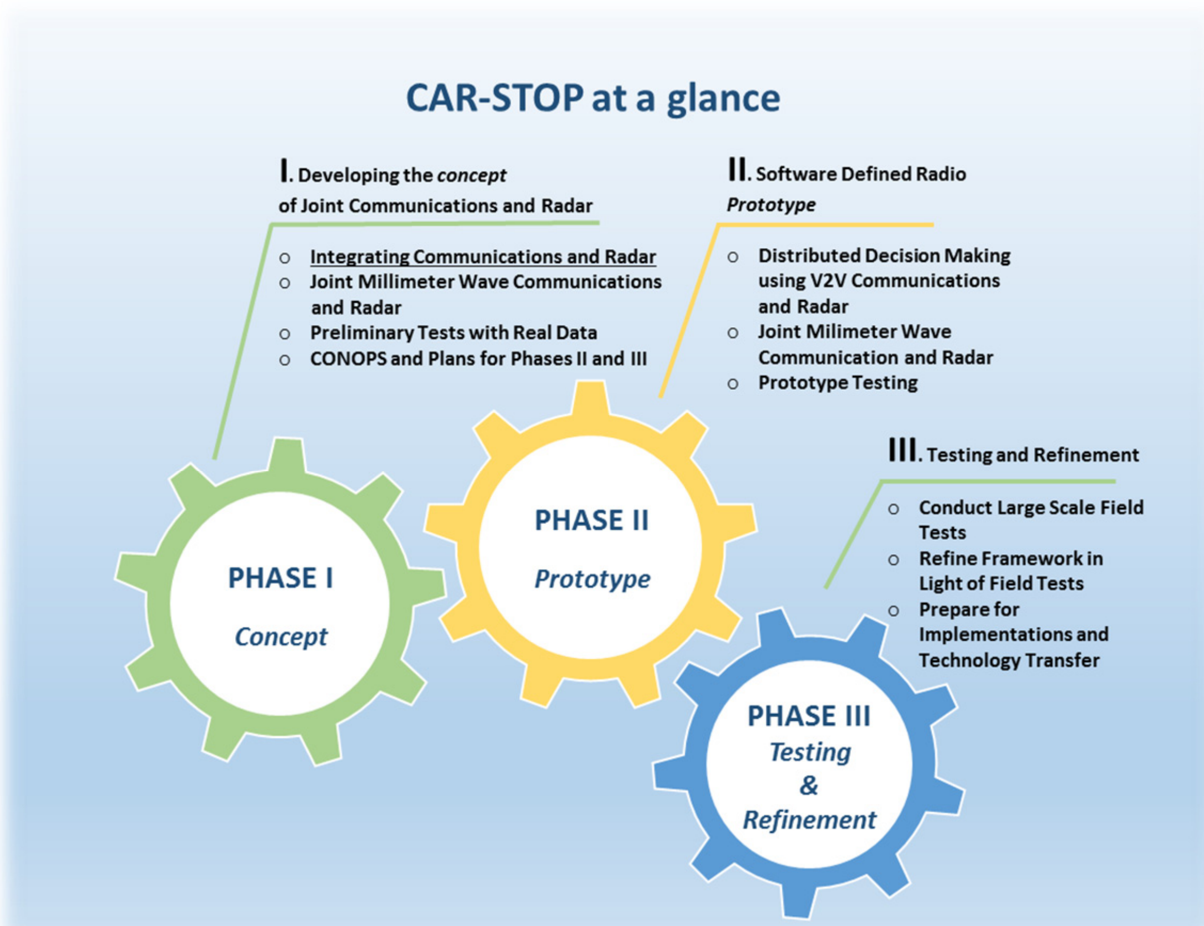

Figure 1: Project idea and objectives for the different phases.

The research team does not anticipate any proprietary deliverables or intellectual property arising from this work.

2. STATEMENT OF WORK (WORK PLAN)

2.1. Project Vision

Crashes represent an enormous cost to society in terms of property damage, productivity loss, injury and even death. Identifying the factors that contribute to crashes and developing countermeasures is therefore a priority for transportation and safety professionals.

Within the context of transportation safety, improving roadway safety is acknowledged as a top transportation priority by TxDOT. Roadway traffic accidents in 2012 alone resulted in 33,561 fatalities and 2.36 million injuries in the country as a whole (NHTSA, 2013)[1], and 3,398 fatalities and 230,506 injuries in Texas (TxDOT, 2013).[2] This translates to an average of one fatality every 2 hours and 35 minutes in Texas, and one reportable crash every 75 seconds in Texas. In fact, motor vehicle crashes continue to be the leading cause of death for people aged 11 through 33 years of age, with no deathless days recorded on Texas roadways in 2012 (TxDOT, 2013). Even if a roadway accident does not involve a fatality, accidents represent an enormous cost to society, including property and motor vehicle damage, productivity losses, medical and administrative expenses, mental trauma, pain, and increased insurance premiums.

The project will represent an interdisciplinary and multidisciplinary effort focusing on research and technology transfer activities to promote the integration of cutting-edge developments in communications and radar technology with transportation systems to improve roadway safety (and thereby also the accessibility and reliability) of the travel experience of Texans. The project will be directed toward (a) improving the use of wireless technologies to obtain data from multiple and heterogeneous sources, (b) machine learning and data driven information extraction capabilities that are localized and timely, and (c) bringing information together with driver characteristics and behavior to develop safety systems that are effective and customized. To be effective, this research must consider the transportation and communications/radar infrastructure systems in a holistic fashion, as well as the relationship between these systems and the social/economic aspects of society that drive how individuals (and groups of individuals) receive and perceive information about travel conditions/events and respond to such stimuli. The investigators of this proposal, drawn from multiple disciplines, have examined these and many other aspects of safety. From the perspective of interactions of driver characteristics and behavior with crash occurrences, the Research Supervisor, a transportation faculty member associated with the Departments of Civil Engineering and Economics, is recognized worldwide as a leader in econometric and statistical analysis techniques that unravel the factors causing aggressive driving behavior (and aggressive teenager driving behavior in particular), and the interactions of roadway geometrics, vehicle attributes, and environmental conditions with road-user behavior

[1] National Highway Traffic Safety Administration - NHTSA (2013). Traffic Safety Fact Sheet, 2012. Publication DOT HS 811392, National Center for Statistics and Analysis, National Highway Traffic Safety Administration, Available at: http://www-nrd.nhtsa.dot.gov/Pubs/811856.pdf

[2] Texas Department of Transportation (2013). Texas Motor Vehicle Traffic Crash Highlights, Calendar Year 2012, Available at http://ftp.dot.state.tx.us/pub/txdot-info/trf/crash_statistics/2012/01_2012.pdf

(including driver, pedestrian, and bicyclist behavior). His safety-related work has resulted in many publications in top safety journals, as well as garnered attention by policy makers and insurance companies. From a wireless communications perspective, the first Co-PI, a wireless networking and communications (WNCG) faculty member from the Electrical and Computer Engineering (ECE) has been a pioneer in communication technologies, especially those that have application in V2V and V2I systems. He has contributed a high number of widely cited papers in the areas of wireless communications and signal processing, including specific topics relevant to this project proposal like MIMO systems (multiple antenna communication) or millimeter wave (mmWave) communications. He has also lead several prototyping projects with top hardware companies in United States. From a machine learning-based perspective, the second Co-PI, also a WNCG faculty member from the Department of Computer Science, is a world-renowned scholar in machine learning and data mining techniques. He specializes in integrating heterogeneous data sources and multiple data analysis methods, including Bayesian and artificial intelligence (AI) approaches, to reliably address complex engineering problems. Figure 2 provides a diagrammatic representation of the expertise involved in the proposed project. Fundamental innovations will occur in the areas of wireless communication, distributed machine learning and decision making, and transportation modeling. The outcomes of the project are expected to dramatically improve safety for vehicles, bicycles, and pedestrians in all weather conditions and on all roadways.

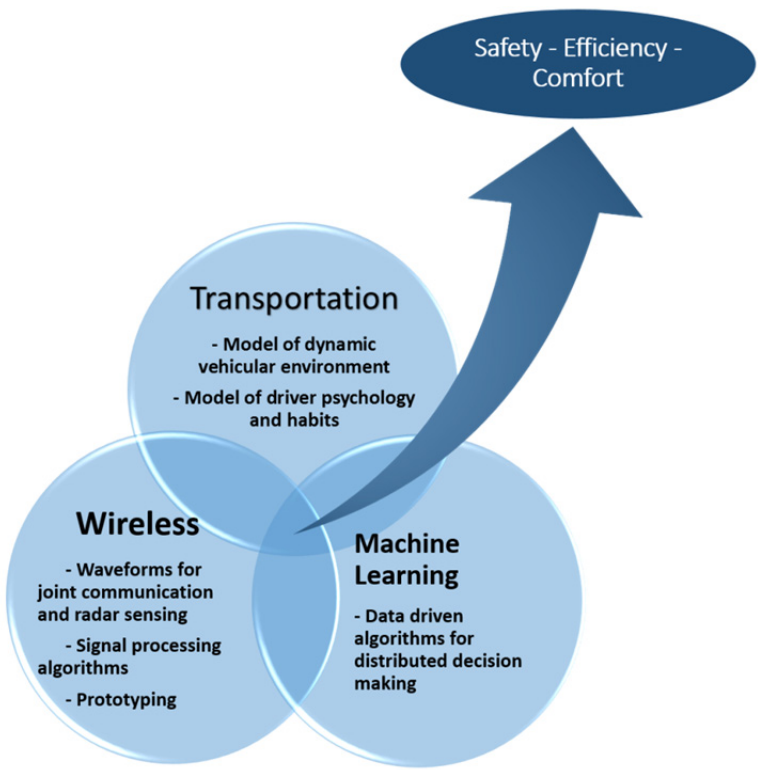

Figure 2: Areas of expertise involved in the project.

2.2. Project Mission

The overarching research mission of the proposed project will be two-fold: (1) Develop a conceptual framework to harness and mature wireless technology to improve transportation safety, with a focus on frontal collision warning/collision avoidance (CW/CA) systems; the framework will identify components of the technology and its capabilities, and how these components can be integrated to improve transportation safety, and (2) Demonstrate the concepts and technologies in a test-bed scenario, and produce a full concept of operations (CONOPS) together with a complete and detailed inventory of the requirements for full deployment in an operational environment. The mission will be realized through technologically innovative and dynamic information-gathering processes and intelligent machine learning systems. The resulting critical knowledge base will advance the field by bringing the full force of emerging technology advances to address transportation safety challenges. The project will disseminate information on research activities and findings, and actively promote the utilization and implementation of research products/findings through demonstrations on small-scale test-bed networks. The test-bed demonstrations, along with discussions with industry and public agency partners, will also enable the team to identify risks and ways to mitigate those risks as concepts are considered for transitioning to the real-world transportation environment.

2.3. Overview of Phase I Plan

The project's research activities will focus on the advancement of the body of knowledge on the use of wireless technology (both communications and radar) to address the transportation safety challenges facing the state. The emphasis will be on both basic research and porting that basic research to applied research in the form of pilot implementation tests. All phases will have a basic research component as well as an applied research component, with Phase I being much more loaded on the basic research/conceptualization component, while Phase III (if the project proceeds to that point) heavily loaded on field implementation testing. The specific tasks we propose in Phase I are as follows (see also Figure 3):

(1) Develop conceptual and functional frameworks for *integrated wireless safety systems that incorporate information derived from both communication and radar platforms*,

(2) Advance and develop *a new combined communication-radar paradigm for automotive applications* using next generation millimeter wave communication,

(3) Conduct *preliminary tests with real data*, develop a *full Concept of Operations* and requirements for full deployment.

(4) Design a complete *research plan for phases II and III* of the project with the objective of developing, testing, and refining an integrated communication-radar unit at mmWave.

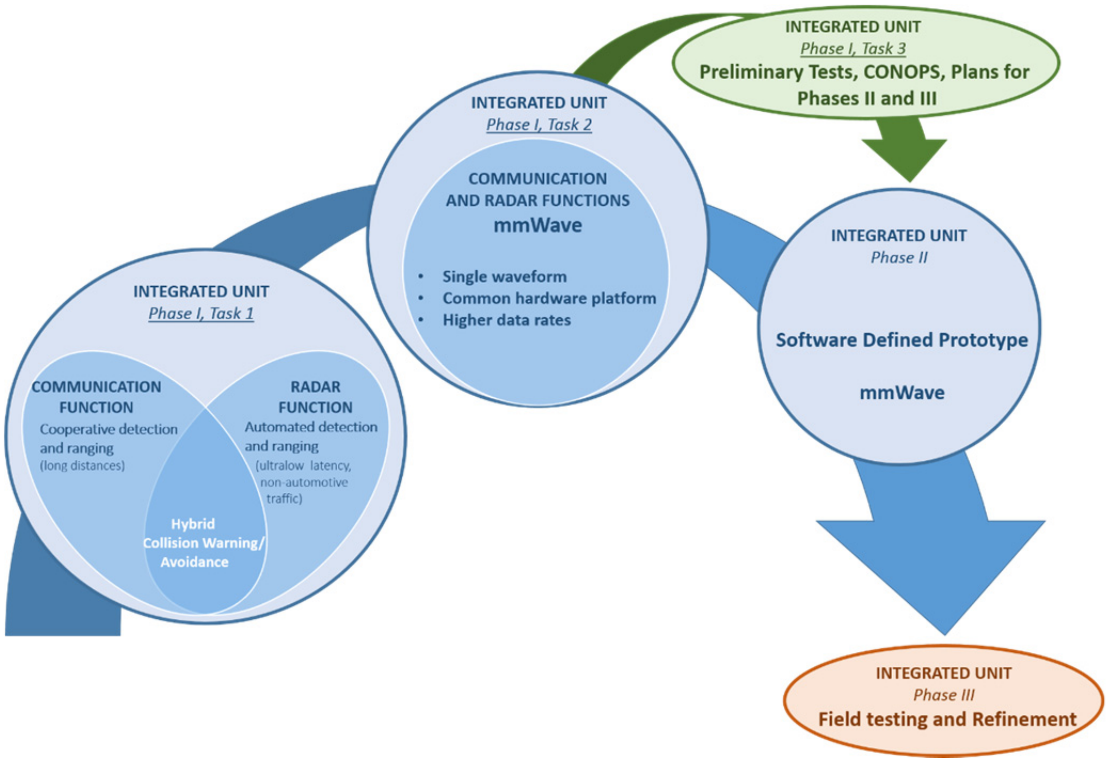

Figure 3: Progression of tasks in the development of an integrated prototype unit for intelligent transportation safety.

A final Phase I report with a project summary report listing all proposed designs and CONOPS to harness radar and communications technology for roadway safety and collision avoidance will be provided, and completed at the end of the work plan, even though we are not explicitly including this as a task in the Phase I work plan (because this task will be pursued in parallel with the tasks identified above).

The prime organization will be the sole organization responsible for the package. National Instruments will act as a consultant on prototyping activities, bringing their experience working with in-car protocols: CAN, FlexRay or LIN. The deliverables will include the following:

(1) A technical memorandum detailing the conceptual and functional frameworks at the end of Task 1 (within 10 months after award)
(2) A second technical memorandum discussing the new combined wireless paradigm at the end of Task 2 (within 10 months after award),
(3) A third technical memorandum formulating CONOPS and detailed plans for Phase II and III research if allowed to proceed (draft within 12 months after award)

In addition, a complete final report and a project summary report will be completed within one year of the project.

2.4. Preliminary Plans for Phases II and III

This section presents the proposal team's preliminary vision for Phases II and III. During the course of Phase 1, the team anticipates substantial learning, both from a technical as well as practical feasibility standpoint, and a detailed plan for Phase II will be delivered to TxDOT for consideration by the 10th month of Phase I.

Phase II: Software defined Radio Prototype

The research developed in this proposal will impact real-world transportation systems. This phase will focus on prototyping efforts that will be used for more extensive data collection, algorithmic demonstration, and proof-of-concept demonstrations. The phase will include the design of an elaborate test-bed and associated experiments to demonstrate concepts, test components, and mitigate risks. A prototype will be developed for each system component and the CA/CW system as a whole, along with designing a virtual transportation system test-bed for functionality testing; this phase will include an experimental design to test scalability effects even if only within the parameters allowed by the test-bed. The experiments will identify the "weak" links of the system in the test-bed environment, and will identify ways to reduce the technical risk associated with the "weak" links of the system through re-designing the functional framework and potentially re-sequencing component operations in space and time. At the end, a revised full Concept of Operations (CONOPS) and requirements for full deployment will be developed.

Total estimated budget for Phase II: $1.9 million over two years.

Task II-1. **Distributed Decision Making using V2V Communications and Radar**

Description: This research task is devoted to further developing a proof-of-concept prototype that integrates communications and radar together and collecting data to inform the algorithmic development. A main breakthrough of this prototype versus prior prototypes [BMFJ12] [ZLW07] [WER04] [NK09] [SNH08] [LK10] will be the integration of commercial off-the-shelf V2V and automotive radar systems to perform joint decision-making. The use of off-the-shelf commercial products lends an element of realism to the prototype effort. It is expected that a major difficulty will be assembling the information on a laptop, given the likelihood of proprietary interfaces in the different commercial V2V hardware [MJ03] and radars [FL08] [AOH+01]. The prototype will be used to collect data and make decisions to show that combining information is possible and leads to more accurate decisions.

Anticipated duration: Months 13-24

Anticipated budget: 30% of Phase II budget

Task II-2. Joint Millimeter Wave Communication and Radar

Description: This research task is devoted to developing a proof-of-concept prototype for joint millimeter wave communication and radar. This will be the first software defined radio millimeter wave prototype to integrate radar and communications together. Because of hardware limitations, prototyping at millimeter wave has been very difficult, especially for communication applications. However, National Instruments is in the final stages of production for a new millimeter wave prototyping platform, which will be ready in early 2015, which is well ahead of the anticipated Phase II start time in November 2015. This platform will support transmission and reception in the E-band around 70 GHz carrier frequencies (very near to the automotive 77 GHz radar) with bandwidths of up to 2 GHz. To facilitate processing, the platform will use an innovative WHAT IS FPGA? FPGA board that can be operated using a special compiled software (instead of writing FPGA code). As a result, it will be possible to rapidly implement different waveforms using a common hardware platform. In addition, National Instruments is working on developing a digitally controlled adaptive array that can work with their hardware platform. This will allow us to experiment with more advanced beamforming adaptation algorithms as we have proposed. Because joint communication and radar at millimeter wave frequencies is in its infancy, this research task will focus on demonstrating that it is possible to combine the two technologies together in a way that leads to mutual benefits, perhaps without the level of integration found in the task on distributed decision making. UT has extensive experience with National Instruments equipment, including developing previous prototypes [GFH04] and developing a complete course on wireless communications using their equipment [hea] [Hea12]. National Instruments engineers will assist with the software development and hardware debugging.

Anticipated duration: Months 19-30

Anticipated budget: 35% of Phase II budget

Task II-3. Prototype Testing

The developed prototype for the joint millimeter wave communication and radar will be installed in three test vehicles. The test vehicles will be different in body type, to examine the effects of vehicular characteristics on the CA/CW system, and to customize parameters of the system for different types of vehicles. An efficient experimental design of critical scenarios will then be created so that the potential effects of individual dimensions as well as combinations of these dimensions as they pertain to the design of the CA/CW system can be extracted. The three vehicles will be used (at low speeds) in the experimental configurations around the prime organization's campus to collect measurement traces. The project team will use the collected data to optimize CA/CW component algorithms for different scenarios as well as to test the performance of individual components and the overall CA/CW system.

Anticipated duration: Months 31-36

Anticipated budget: 35% of Phase II budget (unless cars need to be purchased)

Phase III: Field Testing and Refinement

This phase will focus on further data collection through large-scale field tests, refinement of the proposed framework, and finally technology transfer. The first task will be more extensive field tests of the prototypes development in Phase II, to expand the set of possible scenarios and geometries. The data included in the first step will be analyzed and used to refine the proposed framework, for example to tune model parameters and account for alternative scenarios. The final task will be to transfer the technology to TxDOT and other stakeholders to discuss the framework and project findings, and develop implementation strategies to facilitate deployment as soon as possible following conclusion of the project.

Total estimated budget for Phase III: $1 million over 12 months.

Task III-1. Conduct Large Scale Field Tests

Description: This task involves demonstrating the safety strategies developed by the research team in Phase II. The first subtask in this phase will involve more elaborate testing and prototyping of the integrated communication and radar platform. This will provide practical demonstrations of these strategies for a variety of roadway geometrics, roadway control systems, environmental conditions, and driver characteristics. Unlike the tests undertaken earlier, these field tests will be based on regular travel conditions in different parts of Austin, and will be undertaken with the help of TxDOT and the Department of Public Safety. The second subtask in this phase will involve further testing and prototyping of the joint millimeter wave radar-communication prototype. This includes the construction of additional prototypes, and experimental validation versus the integrated communication and radar platform that does not use a single system.

Anticipated duration: Months 37-45

Anticipated budget: 60% of Phase III budget

Task III-2. **Refine Framework in Light of Field Tests**

In this task, the research team will adjust the strategies, weights of communications and radar-based data, and decision-making frameworks identified in previous tasks based on the results of the field tests. Essentially this will involve several subtasks to tune and optimize the different parameters to operate over a wider variety of operating conditions. These refinements will be based on the extensive field testing undertaken Task III-1 of the project, and also on the robustness of results obtained from the earlier phases of the project. It is possible that some scenarios (such as snow conditions) may not be represented in the field testing, but it may be important to examine the performance of the proposed CW/CA system in these conditions too. Thus, Task III-2 will also involve undertaking simulation experiments to accommodate conditions not represented in the field testing data.

Anticipated duration: Months 43-46

Anticipated budget: 20% of Phase III budget

Task III-3. Prepare for Implementation and Technology Transfer

This final task will involve meetings with TxDOT and stakeholders to discuss the framework and project findings, and develop implementation strategies to facilitate deployment as soon as possible following conclusion of the project. Final reports and deliverables will be written, and additional technology transfer activities (such as workshops, brochures, or training materials) will be developed.

Anticipated duration: Months 45-48

Anticipated budget: 20% of Phase III budget

3. DETAILED PHASE I PLAN

This section provides full details on all Phase I activities, to level 3 (task, subtask, and work package). Please note the following:

1. All tasks, subtasks, and work packages will be completed by the prime organization. This project will involve National Instruments for help with equipment and data procurement.
2. The dependencies listed below show the most important and critical links between activities and their prerequisites; however, the research team will adopt an integrated view of all tasks, and look for insights from each work activity that could be applied to other concurrent and future activities.
3. The cost estimates below include student tuition. While this tuition must be charged at the start of each semester, for the purpose of the cost estimates this cost is amortized based on relative student effort on each work activity, regardless of the timing of each work activity in the context of the semester schedule.

Task 1: Conceptual and Functional Framework for Integrating Communications and Radar

Duration: Months 1-10

General description: This research task is devoted to the development of a conceptual and functional framework for the integration of information derived from communications and radar to make more accurate decisions. The emphasis of the procedures (i.e., algorithmic development) here for integration will be on the important problem of frontal collision warning/collision avoidance (CW/CA) systems, though the approach taken here will also apply to other problems such as traffic management and coordination, and automatic cruise control. Emphasis is placed on CW/CA because of (1) its importance to improve safety in automotive systems [Nat] and (2) both communications and radar can be used to implement a CW/CA system. We will take a data-driven approach where the information gleaned from communication and radar systems are combined together to make a more accurate and lower latency CW/CA system. This involves transportation modeling, human behavior analysis, distributed decision making, and machine learning.

Detailed description: This task consists of two subtasks: (1) Develop improved collision detection and avoidance algorithms for cars, and (2) Develop improved collision detection and avoidance algorithms for bicycles and pedestrians. In each of these tasks, the multiple dimensions of communications and radar systems, and the interactions of these dimensions with human behavior will be identified, and a framework for an integrated communications-radar system that accommodates driver reactions and behavior in the context of frontal CW/CA will be developed. More details can be found in the subtask and work package descriptions below.

Dependencies: None

Completion criterion: This task will be complete when the research team has developed a comprehensive conceptualization and functional framework for the CW/CA system, including algorithms for minimizing, and reducing the consequences of, vehicle-vehicle crashes as well as vehicle-pedestrian and vehicle-bicyclist crashes.

Deliverables: Upon completion of this task, the research team will produce a technical memorandum (TM-1) summarizing the completion criteria. This memorandum will be provided in electronic form to TxDOT (PDF or similar format.) This deliverable is due 15 days after conclusion of Task 1 (3.5 months after award.)

Technical Rationale: This task is the fundamental basis for all other subsequent tasks. Additional details are provided in the technical rationales for subtasks and work packages.

Basis of Estimate: The assigned budget for this task (including all subtasks and work packages) is $270,800. This involves $72,405 for professional staff (0.4 months @ $17,187/mo; 0.4 months @ $15,620/mo; 0.4 months @ $18,198/mo; 9.6 months @ $4167/mo; 1.2 months @ $10,000/mo); $77,280 for graduate student assistants (19.2 PhD student-months @ $2075/mo.; 19.2 MS student-months @ $1950/mo.), $8,152 for administrative staff (1.2 months @ $5404/mo. and 0.4 months @ $4167/mo; this is for non-routine duties related to scheduling project-specific meetings, taking meeting minutes and preparing monthly progress reports, and compiling work package and subtask results into the technical memorandum deliverable); $45,773 fringe benefits (29% of labor), $36,534 tuition for the graduate student assistants; $1959 for general supplies; $800 for phone and internet; $1600 for reproduction costs; $3000 for computer systems support; $2000 for project-related travel, $21,297 overhead (10% of all expenses excluding tuition).

Test and Demonstration Plan: This task is associated with defining (refining) the scope of the project and is not associated with tests or demonstrations.

Subtask 1.1: Develop improved collision detection and avoidance algorithms for cars

Duration: Months 1-6

General description: A collision warning system design should be responsible for monitoring individual driver reactions, predicting consequences of such actions, and identifying if a collision avoidance maneuver is necessary so as to communicate the situation in a timely manner to the driver for a safe evasive action. A poorly designed and overly sensitive system can increase driver's workload, which as a result can decrease a driver's situational awareness, comfort, and safety [VE03]. We propose to develop robust collision detection and avoidance algorithms for cars using information derived from both communication and radar systems, as shown in Figure 4. The technical challenges here relate to combining the heterogeneous information derived from the communication and radar systems, and incorporating vehicular dynamics along with the particular behavior of each driver. As an example of the heterogeneous information available for decision making, each car might have its own state information (position, velocity, trajectory), accurate information about local vehicles using automotive radar, and delayed (less accurate) information about vehicles that are further away using V2V. Based on this information, which is continuously collected over time, each car implements a distributed decision-making algorithm to declare a possible collision and passes the relevant information to another (existing, not part of this proposal) algorithm that determines the evasive action.

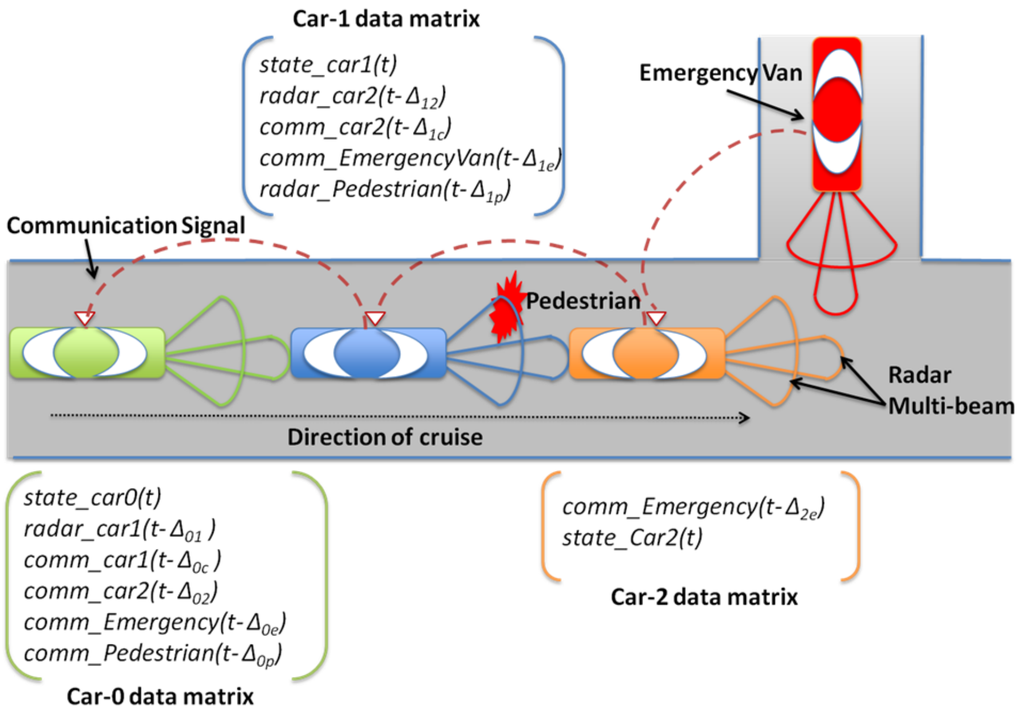

Figure 4: Approach integrating radar and communications for improved CW/CA.

Detailed description: A key aspect of this subtask is to develop advanced machine learning methods that make the algorithms continually evolve and adapt to the behavior of the specific driver and to novel traffic situations that were not present in the training set used to design the initial algorithms. It has been shown that even in simple situations and with very basic information about drivers, such as expertise level and tendency to speed, learning based algorithm provide superior trajectory (and hence collision) forecasting abilities, with tighter probability estimates [SLRK07, ADSH11]. Moreover, driver behavior can be modeled quickly using online algorithms, and quickly deployed for prediction purposes [AH96]. Moreover, the driver often implicitly makes her/his identity known, for example when a Bluetooth connection to her/his phone is made, and so even more accurate models can be built over multiple trips. Bayesian approaches to predicting response times in different situations, including different times of the day allow observed driving behavior to update the “prior probabilities” of such values based on a broader population of drivers, to more accurately reflect the current driver. The Research Supervisor has been at the forefront of traveler behavior analysis and modeling in the field, with all archived journal publications in this area, and the second Co-PI has contributed significantly to the development and deployment of a variety of Bayesian learning and other statistical pattern recognition algorithms. He has also worked on the optimization of the trade-off between missing detection of potential hazards and false alarms when using such techniques.

Overall, the algorithms developed in this phase will improve CW/CA systems by improving reliability, reducing false alarms, and adapting to the specific behavior of people driving the cars, as well as general population behaviors of other road users (including bicyclists and pedestrians, as discussed further below).

Dependencies: None

Completion criterion: This subtask will be complete when the research team has developed methods and algorithms for fusing the heterogeneous information derived from the communication and radar systems, and incorporating vehicular dynamics along with the particular behavior of each driver, to improve collision detection and avoidance.

Deliverables: No specific deliverables will be associated with this subtask.

Technical Rationale: This subtask provides the analytic basis to develop CW/CA systems. Additional details are provided in the technical rationales for the work packages.

Basis of Estimate: This subtask will constitute 40% of the effort and resources corresponding to Task 1. The assigned budget for this subtask (including all work packages) is $108,320.

Test and Demonstration Plan: This subtask will involve some limited testing of the algorithms and machine learning approaches, for functionality.

<u>Work Package 1.1.1: Combining information from the communication and radar systems.</u>

Duration: Months 1-6

General Description: The central goal for this package is to determine the best way to combine information from the two types of information sources, communication and radar, for distributed decision making.

Detailed Description: This is essentially a problem of distributed sensor fusion. Fusion can take place at feature, model construction or model output levels [Das94], and a central goal of this work-package is to determine which level(s) are the most suitable for the CD/CA talks. Another key aspect is to determine the time resolution at which these sources will be sampled. Too frequent a sampling rate will not yield additional resolution while consuming more computation and communication resources. Information theoretic concepts along with simple sequential Bayesian updating procedures will be used for this study [AM09]. This also requires a simulation testbed that produces realistic communication and radar signals, and the platform developed by the first Co-PI over several years shall be adapted for this purpose. It is anticipated that the sampling rate, and the associated communication requirements will depend on both the sensor type and the V2V and V2I distances that are involved.

Dependencies: None

Completion criterion: Tradeoff studies at different levels of sensor fusion and different sampling and communication rates that clearly indicate the optimum operating regimes.

Deliverables: No specific deliverables.

Technical Rationale: Both communication and radar contain information about common environmental sources. Machine learning and data mining techniques will be used to uncover these correlations and to identify lower dimension features.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 1.1. The assigned budget for this work package is $54,160.

Test and Demonstration Plan: There will be no formal testing or demonstration.

Work Package 1.1.2: Incorporating vehicular dynamics and driver behavior

Duration: Months 1-6

General Description: Contextual factors relating to driver characteristics, roadway conditions and geometrics, environmental factors, and vehicle characteristics play an important role in the probability of a crash occurring (on straight stretches as well as intersections). These contextual factors will be carefully examined, and ways to incorporate them into CA/CW systems will be explored and implemented.

Detailed Description: Two important attributes in designing roadway elements from a safety standpoint are the acceleration/deceleration capabilities of the vehicle and the perception reaction time of the driver. In the context of CW/CA systems, these two attributes play an important role in braking distance (that is, the time it takes to come to a stop or to reduce speed adequately before a collision). Of course, the acceleration/deceleration characteristics of the vehicle, in turn, is affected by the coefficient of friction between the vehicle tires and the pavement, which is itself influenced by the pavement material type, environmental factors (such as rainy or snowy conditions, or normal weather), and how hard the driver presses down on the brakes (as well as the performance parameters of anti-lock braking systems installed on the vehicle). Similarly, the perception reaction time of the driver is a function of driver characteristics and behavior (such as age, cognitive awareness levels, aggressiveness nature of the driver, and focus level of driver), environmental factors (day or night, weather conditions, etc.), and driving context (for example, perception-reaction time is higher when a person suddenly cuts in front as opposed to when approaching a signalized intersection; similarly, perception-reaction time is shorter when approaching urban signalized intersections rather than when approaching rural signalized intersection). The Research Supervisor has undertaken many roadway crash frequency and crash injury severity studies (for example, see [MB14], [BBSB14], [CPB13], and [APB13]) considering all of the contextual factors discussed above. In the current task, the design of the CW/CA system will be customized to handle the many contextual situations based on these earlier studies, with additional fine tuning and testing undertaken during the actual prototyping and testing in Phases II and III.

Dependencies: None

Completion criterion: Customizing the sampling/communication rates and sensor fusion levels to contextual driving conditions accounting for vehicular and driver characteristics.

Deliverables: None.

Technical Rationale: Contextual factors play a key role in avoiding frontal collisions, and must be considered in any CA/CW system design.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 1.1. The assigned budget for this work package is $54,160.

Test and Demonstration Plan: There will be no formal testing or demonstration. Context-specific customization will be based on the results from earlier studies. Additional testing with easily available or collectible data will be considered in Task 3 to inform the customization.

Subtask 1.2: Develop improved collision detection and avoidance algorithms between cars and non-motorized road users (bicycles and pedestrians)

Duration: Months 6-10

General Description: Cars are only a fraction of the users of roadways. Other sources of traffic include trucks, motorcycles, scooters, bicyclist, and pedestrians. Each source of traffic is endowed with different degrees of technology and it is not reasonable to expect them all to have a common base of capabilities. We propose to develop improved collision detection and avoidance algorithms for cars with an emphasis on dealing with other road users (pedestrians and bicyclists).

Detailed Description: When considering interactions between cars and other road users, radar becomes even more important to derive information about the surroundings of a vehicle. Communication though will still be valuable. For example a vehicle several vehicles away may detect the presence of a pedestrian and may communicate this information to other neighboring vehicles. This forms a statistical prior that can be exploited by other vehicles (for example, there was a person here waiting to cross the street a minute ago, so I should be extra careful at the intersection). This research subtask will involve developing algorithms for detecting the presence and position of pedestrians and bicyclists. Several simulation studies have shown that machine learning provides improved performance in such situations as well [SLRK07a, AFG13]. Established computer vision oriented methods for pedestrian representation and detection can be adapted to incorporate radar signals [CZQ05]. A variety of evaluation metrics have already been developed [LP05], and are useful to compare our methods with existing approaches suggested by researchers at Mazda, Honda, JHU and Jaguar. In addition to data generated from our distributed simulation platform, there are several public domain datasets that will be used for comprehensive evaluations [MHD08].

In addition, we will also consider the role that communication can play in forwarding the information from learning based predictive algorithms (in the form of tentative decisions) to other vehicles to enable them to further improve their own collision detection and avoidance algorithms, especially (but not exclusively) for avoiding conflicts with non-motorized road users. This subtask will improve the safety of non-vehicular users of roadways.

Dependencies: There will be clear dependencies between all subtasks within Task 1, as all of these focus on information extraction through data fusion, using machine learning methods and algorithms. In addition, there will be dependencies because of the consideration of vehicular and non-vehicular road users in the system, and the interactions among the different road-users.

Completion criterion: This subtask will be complete when the research team has developed methods and algorithms for fusing the heterogeneous information derived from the communication and radar systems, and incorporating vehicular dynamics along with the particular behavior of drivers as well as other road users, to improve collision detection and avoidance.

Deliverables: No specific deliverables will be associated with this subtask.

Technical Rationale: This subtask provides the analytic basis to develop CW/CA systems. Additional details are provided in the technical rationales for subtasks and work packages.

Basis of Estimate: This subtask will constitute 30% of the effort and resources corresponding to Task 1. The assigned budget for this subtask (including all work packages) is $81,240.

Test and Demonstration Plan: This subtask will involve some limited testing of the algorithms and machine learning approaches, for functionality.

<u>Work Package 1.2.1: Incorporating radar signals to computer vision oriented methods for pedestrian and bicycles detection.</u>

Duration: Months 6-10

General Description: Radar signals will enhance "perception" of depth or distances as well as of motion as compared to relying only on computer vision methods.

Detailed Description: Since non-motorized road users in general will not be equipped with wireless devices that communicate with vehicles in the vicinity, computer vision techniques are helpful for identification and tracking of such users. Radar provides a supplementary source of information regarding depth and motion and can be used to enhance the vision based algorithms. This is particularly helpful when there is much occlusion of objects or when several objects cross in the field of view, thus challenging the object tracking algorithms. This is a problem of sensor fusion based decision making. The work-package will determine the most reliable way of combining the complementary information sources in a distributed environment, and specifically how to combine the predictions (and associated uncertainties) from different sources.

Dependencies: As mentioned earlier, there will be clear dependencies between all subtasks within Task 1, as all of these focus on information extraction through data fusion, using machine learning methods and algorithms. In particular, this work package will be dependent on the previous subtask that considers vehicular and non-vehicular road users in the system, and the interactions among the different road-users.

Completion criterion: This work package will be complete when the research team has developed methods and algorithms for fusing the heterogeneous information derived from the radar and computer vision systems, and quantifying its effect in further improving collision detection and avoidance.

Deliverables: No specific deliverables will be associated with this work package.

Technical Rationale: Communication, radar and visual sources of information need to be combined synergistically in order to develop robust CW/CA systems.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 1.2. The assigned budget for this work package is $40,620.

Test and Demonstration Plan: None.

<u>Work Package 1.2.2: Designing a V2V communication strategy to improve CW/CA algorithms</u>

Duration: Months 6-10

General Description: Existing V2V communication systems exchange information with low latency for collision detection and avoidance. They do not yet exploit the ability to further propagate information for the purpose of more advanced CW/CA algorithms that can be especially useful for avoiding collisions with non-motorized road users. This task explores what other information should be communicated to improve CW/CA algorithms.

Detailed Description: Subtask 1.1 develops improved collision detection and avoidance algorithms for cars, based on existing information that is already available. This WP considers what additional information can be exploited to further improve the CW/CA algorithms. In particular, the team envisions that features propagated from multiple cars ahead will be important. Essentially, the idea is that information derived or computed at one car (for example the results of radar or tentative decisions made from the machine learning algorithm) could be used by subsequent cars to improve the performance of their CW/CA algorithms. Essentially this information creates a *prior* which give statistical information that is used by algorithms to bias the potential decision. If a car that is several cars ahead in the traffic detects a bicycle with its radar, then it is likely that subsequent cars will also detect that same bicycle. Their sensors can be aware of this potential and the algorithms can be tuned to be extra mindful. This WP looks at the benefits of information derived from cars that are several car lengths away, also known as the multi-hope scenario where information hops from vehicle to vehicle. The value of that information on the performance of the proposed CW/CA algorithms will be established, with the objective of finding the compromise between the amount of information propagated and the latency of that information.

Dependencies: Depends on the algorithms derived in Subtask 1.1.

Completion criterion: Additional feature sets are identified that improve the performance of CW/CA algorithms.

Deliverables: None.

Technical Rationale: The rationale for this work package is that information gleaned by proximal vehicles can be beneficially used to improve information latency and the performance of the CW/CA algorithms.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 1.2. The assigned budget for this work package is $40,620.

Test and Demonstration Plan: This work package will involve some limited testing of the algorithms and machine learning approaches, for functionality.

Subtask 1.3: Dealing with uncertainty (caused, for example, by delays in the communication and inconsistency in data sources) and harnessing the power of collective intelligence

Duration: Months 6-10

Overall Description: Uncertainty in the state information is a common theme in the research phases proposed in this task. Sources of uncertainly include delays (on average 3-7.4 ms of latency per hop for V2V communication [CO11]), imperfect decisions (no radar system is perfect), and lost packets (due to propagation and fading in the wireless communication channel). Algorithms will be developed that are robust in the presence of different forms of uncertainty.

Detailed Description: It will be necessary to develop statistical models for the different types of uncertainty. From these models, it should be possible to obtain *reliability values associated with the different types of data*, so that every data driving the decision making process will be linked to a reliability value. The reliability in turn will depend on the level and nature of the uncertainty and will be used to obtain the corresponding weight of that data into the equation driving the decisions. Algorithms to estimate reliabilities for the different types of data will have to be developed, in addition to expressions for the weights in terms of the reliability estimates. Bayesian approaches are favored here since they can yield confidence intervals with every estimated parameter and thus quantify the associated uncertainty. In addition to reliability, *availability of data* should also be considered to prevent the algorithm failure due to the temporal unavailability of one of the data streams that is input to the decision making process.

Dependencies: There will be clear dependencies between all subtasks within Task 1.

Completion criterion: This subtask will be complete when the research team has developed methods and algorithms for quantifying uncertainty from different data sources, and obtaining weights for data fusion.

Deliverables: No specific deliverables will be associated with this subtask.

Technical Rationale: This subtask is another integral element of the analytic basis to develop CW/CA systems. Additional details are provided in the technical rationales for subtasks and work packages.

Basis of Estimate: This subtask will constitute 30% of the effort and resources corresponding to Task 1. The assigned budget for this subtask (including all work packages) is $81,240.

Test and Demonstration Plan: This subtask will involve some limited testing of the data fusion algorithms and machine learning approaches, for functionality and accuracy testing. Additional preliminary testing will be undertaken later in Task 3.

Work Package 1.3.1: Developing statistical models for the different types of uncertainty

Duration: Months 6-10

General Description: Uncertainty can arise from data that is randomly missing or missing in a systematic way that will create a bias in estimations that are based on it. It can also be due to measurement or transmission errors. Any statistical model based on such data cannot produce purely deterministic answers. So the goal of this effort is to minimize the uncertainty in CW/CA and related decision making given the imperfect nature of signals.

Detailed Description: Both vehicular and non-vehicular motion show piecewise smooth trajectories most of the time. Such smoothness is encouraged in statistical models by adding a penalty for deviations from expected trajectories, through a process called regularization. Abrupt changes such as hard breaking are modeled by temporarily disabling such penalties. A unifying principle that will be followed to deal with uncertainties is to predict expected behavior (position, velocity, etc.), and focus on deviations from such behavior. It is anticipated that in most situations, the smoothness principle will be supported by the available data in at least one modality. Our simulations will determine which modalities to trust – quantified by giving reliability weights – and to what extent in various situations where the uncertainty casts a doubt on the default smoothness based estimates.

Dependencies: This work package depends on Subtasks 1.1 and 1.2 to be at or near completion so that the uncertainty handling mechanisms can be demonstrated in realistic environments reflecting both radar and communication links in place.

Completion criterion: This work package will be complete when the research team has developed methods and algorithms for quantifying uncertainty from different data sources, and obtaining weights for data sources, and confidence intervals from data fusion results.

Deliverables: No specific deliverables will be associated with this work package.

Technical Rationale: The variety of uncertainties that are encountered in smart transportation systems demand a broad set of statistical techniques to mitigate their effects to negligible levels.

Basis of Estimate: This work package will constitute 30% of the effort and resources corresponding to Subtask 1.3. The assigned budget for this work package is $24,372.

Test and Demonstration Plan: This work package will involve some limited testing of the data fusion algorithms and machine learning approaches, for functionality and accuracy testing

<u>Work Package 1.3.2: Introducing reliability and availability of data into the decision making process</u>

Duration: Months 6-10

General Description: Additional sources of reliable and available data reduce the uncertainties in various steps that lead to decision making, but at increased cost. Clearly there are diminishing returns and so one needs to determine how rich different data sources need to be to guarantee overall system reliability to acceptable levels.

Detailed Description: It is well known that averaging K independent estimates of a value reduces the variance of the estimate by a factor of K. If the estimates are correlated, then the gains are reduced and a bias is added. In smart transportation systems, we are interested not so much in the accuracy of different measurements but rather than in the quality of predictive models for decision making based on such measurements. This can be mathematically estimated for linear models, but warrant simulation studies for non-linearly interacting systems. This work package will center around such simulation studies and quantify how the reliability changes with the number and quality of different signal sources.

Dependencies: This work package depends on Subtasks 1.1 and 1.2 to be at or near completion and has to be performed in parallel with Work Package 1.3.1.

Completion criterion: This work package will be complete when conclusive simulation results are obtained.

Deliverables: No specific deliverables will be associated with this work package.

Technical Rationale: This effort is needed to determine cost-effective solutions for intelligent transportation infrastructure, and to determine where the points of severely diminished returns are reached as added radar/communication resources are harnessed.

Basis of Estimate: This work package will constitute 30% of the effort and resources corresponding to Subtask 1.3. The assigned budget for this work package is $24,372.

Test and Demonstration Plan: None.

<u>Work Package 1.3.3 Collective intelligence: A principled framework for distributed decision making</u>

Duration: Months 6-10

General Description: Safe and efficient transportation is intrinsically a collective and cooperative operation: if every car tried to optimize its own goals without regard to others, chaos and mayhem results. A fundamental challenge in such situations is to design a multi-agent system such that even if each agent is self-centered and only tries to optimize its own reward, a globally defined criterion also gets optimized.

Detailed Description: For over a decade, the members of the UT team have been actively involved in developing a mathematical framework called "collective intelligence", which uses reinforcement learning to develop a collective and cooperative agent system called COIN [TW04, TA07]. It systematically designs the reward functions for each agent such that self-centered behavior gets aligned to global good, and has been deployed to address complex coordination tasks including air traffic control, as vetted by NASA [TA07]. In this task, our previous work will be combined with other relevant research to develop a framework that will be the cornerstone for our distributed decision making platform for transportation safety. Specifically, in CW/CA systems, a global objective function is to expedite traffic flow subject to over-riding constraints on safety. In COIN, this objective function will be used to derive local objective functions, one for each object of interest. These objects then make moves to as to optimize their own objectives, i.e., behave like selfish agents. The COIN framework, however, guarantees that in the process the global objective is also met. This allows the agents to work in a very independent fashion, and reduces communication requirements.

Dependencies: There are clear dependencies between this work package and earlier ones within Task 1, as information extraction through data fusion should be combined with a distributed framework that provides information in such a way that it is for the global good (in the current case, minimizing crashes).

Completion criterion: This work package will be complete when the research team has developed methods and algorithms for the collective intelligence framework for distributed decision-making for transportation safety applications.

Deliverables: No specific deliverables will be associated with this work package.

Technical Rationale: This work package is another integral element of the analytic basis to develop CW/CA systems. Additional details are provided in the technical rationales for subtasks and work packages.

Basis of Estimate: This work package will constitute 40% of the effort and resources corresponding to Subtask 1.3. The assigned budget for this work package is $32,496.

Test and Demonstration Plan: This work package will involve some limited testing of the collective decision framework here and later in Task 3, though the focus will be on the conceptualization of such a framework.

Task 2: Developing Joint Automotive Radar and Communication at the mmWave Band

Duration: Months 1-10

Overall description: The millimeter wave band (roughly from 30 GHz to 300 GHz) is used extensively in automotive radars. Until 2013, automotive radars were predominately used at 77 GHz and 24 GHz [Sch05]. The frequency band at 79 GHz is now emerging in place of the 24 GHz band [CPA] [HTS+12]. Millimeter wave radar provides a high-resolution (range, velocity and angle), low-latency, small-antenna size and single chip & packaging solution to meet the requirements of driver assist functions. This would in turn, for example, help high-speed vehicles better detect a pedestrian or a bicycle. There is a substantial opportunity to combine radar and communication concepts together into one joint waveform at millimeter wave frequencies. This will allow a single signal to be used both for radar purposes and for V2V or V2I, offering the added benefit of much higher data throughputs.

Detailed Description: Recently, millimeter wave systems have been developed for consumer wireless communication products at 60 GHz [RHDM14]. The first systems available were used for cable replacement for home theater systems [PCPY10] [YC07] [Kri07]. More recently, millimeter wave has also been incorporated into wireless local area networks through IEEE 802.11ad, WiGig [Han11] [WiG], ECMA TC48 [ECM], IEEE 802.15.3c [IEE] and WiHD [WiH]. It is expected that millions of devices will be shipping by the end of 2014. The implications of using millimeter wave for consumer devices is that cost is expected to plummet (note that wireless local area network access points cost around $100, while automotive radar systems cost around $1,500). More exciting is that millimeter wave is now being considered for cellular applications [RHDM14] [BHJ14] [RSM+13] [PK11] at other frequencies LMDS bands (27.5-28.35 GHz, 29.10-29.25 GHz, 31.075-31.225 GHz), 38GHz (38.6-40GHz) and 40GHz (40.5-42.5) bands, and E-band (71-76, 81-86, 92-94, 94.1-95) [PK11]. The first Co-PI has made several innovations in the area of millimeter wave communication [MH14] [AALHJ14] [EAHRP13] [AEALH13] [EARAS+13] [EAHAS+12] [BHJ14] [BDH14] [BHJ13] [AEAH12] including co-authoring a comprehensive textbook on the subject [RHDM14].

Because the bandwidths at millimeter wave are much higher (hundreds of megahertz versus the 75MHz megahertz in the 5.9 GHz band for WAVELAN [Ken] 75 MHz instead of ten) this will dramatically increase the data rates possible between cars allowing up to 100X more information to be exchanged along with latencies that are 100X lower. Costs will be lower since communication and radar can share a common hardware platform. This could also increase the penetration rate of vehicular communication system [SW11]. This research task deals with the development of joint automotive radar and communication in the millimeter wave band.

Dependencies: There are clear dependencies between this task and Task 1, as the frameworks developed in Task 1 will continue to be used, but at the mmWave Band.

Completion criterion: This task will be complete when the research team has developed a joint automotive radar and communication system at the mmWave band level.

Deliverables: Upon completion of this task, the research team will produce a technical memorandum (TM-2) summarizing the completion criteria. This memorandum will be provided in electronic form to TxDOT (PDF or similar format.) This deliverable is due 15 days after conclusion of Task 2 (9.5 months after award.)

Technical Rationale: This task is another integral element of the analytic basis to develop CW/CA systems. Additional details are provided in the technical rationales for subtasks and work packages.

Basis of Estimate: The assigned budget for this task (including all subtasks and work packages) is $270,800. This involves $72,405 for professional staff (0.4 months @ $17,187/mo; 0.4 months @ $15,620/mo; 0.4 months @ $18,198/mo; 9.6 months @ $4167/mo; 1.2 months @ $10,000/mo); $77,280 for graduate student assistants (19.2 PhD student-months @ $2075/mo.; 19.2 MS student-months @ $1950/mo.), $8,152 for administrative staff (1.2 months @ $5404/mo. and 0.4 months @ $4167/mo; this is for non-routine duties related to scheduling project-specific meetings, taking meeting minutes and preparing monthly progress reports, and compiling work package and subtask results into the technical memorandum deliverable); $45,773 fringe benefits (29% of labor), $36,534 tuition for the graduate student assistants; $1959 for general supplies; $800 for phone and internet; $1600 for reproduction costs; $3000 for computer systems support; $2000 for project-related travel, $21,297 overhead (10% of all expenses excluding tuition).

Test and Demonstration Plan: This task focuses on the conceptualization and basic functionality testing of an integrated framework at the mmWave band level.

Subtask 2.1: Develop a framework for joint millimeter wave communication and radar

Duration: Months 1-6

Overall Description: This subtask is devoted to developing a common waveform format that permits both communication and radar. Waveforms for radar have special structure to permit accurate measurement of distance, direction, and velocity [Coo12] [LM04] [Sko70] [Fri07] [RM01] [Gin12]. Communication waveforms are designed to send as much information as possible in a given amount of spectrum [Gol05]. In many cases these are competing objectives as sending more information may lead to less accurate position and velocity measurements. The goal of this phase is to develop a tunable waveform design for both communication and radar.

Detailed Description: This subtask involves understanding the tradeoffs between radar and communication [Bli14]. After further analysis that refines the tradeoffs, specific waveform designs and corresponding signal processing algorithms will be developed where the objectives of radar and communication can be mutually achieved. For example, the waveform might be divided into a radar portion and a communication portion. Further, the radar algorithms might make use of the communication portion to improve performance while the communication algorithms might use the radar signal for better communication, e.g. an improved channel estimate. This subtask will result in new advances in joint communication and radar at the mmWave band, which can be exploited to develop CW/CA systems.

Several challenges will be solved to enable the joint communication and radar vision. An analytical framework will be developed for joint communication and radar that describes their mutual dependencies. This framework will be used to design the transmitted waveforms and corresponding signal processing algorithms that can be tuned dynamically based situational awareness to offer either higher data rates or better precision location. Antenna arrays will be incorporated into the framework and used to achieve higher link performance and better tracking capability. Finally, security issues will be examined by considering ways to leverage the large antennas to randomize the interference.

Dependencies: None

Completion criterion: This subtask will be complete when the research team has developed a flexible framework for joint millimeter wave communication and automotive radar.

Deliverables: None.

Technical Rationale: This subtask is another integral element of the analytic basis to develop CW/CA systems. Additional details are provided in the technical rationales for subtasks and work packages.

Basis of Estimate: This subtask will constitute 40% of the effort and resources corresponding to Task 2. The assigned budget for this subtask (including all work packages) is $108,320.

Test and Demonstration Plan: None. This subtask focuses on the conceptualization of an integrated framework at the mmWave band level.

Work Package 2.1.1: Studying the tradeoffs between radar and communication.

Duration: Months 1-4

General Description: The goal for this package is to determine analytical tradeoffs between radar and communication waveforms. Metrics of performance include parameter estimation error (related to radar) and data throughput (related to communication link performance).

Detailed Description: Radar systems and communication systems are developed with different end objectives. The waveforms used for each system and therefore designed with other underlying metrics in mind. The objective of this study is to understand how parameters of the waveform relate to radar and communication efficiency. Based on other work reported in the literature [Bli14], there is already evidence that efficiency in both dimensions cannot be achieved simultaneously. For example, sending high information rates requires pulses that carry information to be close together. Accurately detecting position and velocity, however, generally requires pulse that are spread far apart and that carry redundant information. This study will examine these tradeoffs as a way to describe the set of feasible operating conditions, to set the stage for subsequent dynamic operation within that set.

Dependencies: None.

Completion criterion: Tradeoff studies that identify how choice of common parameters impacts radar and communication performance.

Deliverables: Report on the analytical tradeoff study.

Technical Rationale: Communication and radar are both deep mathematical topics, which are often studied independently. Combining their analysis together in a common framework is a natural approach to capture the joint dependency.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 2.1. The assigned budget for this work package is $54,160.

Test and Demonstration Plan: There will be no formal testing or demonstration. The tradeoff study will be augmented by numerical simulations to derive intuition from the mathematical concepts.

Work Package 2.1.2: Designing joint waveforms and signal processing algorithms.

Duration: Months 4-6

General Description: The goal for this package is to design waveforms that solve objectives of both communication and radar. The outcome will be a mathematical description of the transmitted waveforms and associated signal processing algorithms for transmission and reception of the waveforms.

Detailed Description: Combining radar and communication together entails creating a common waveform that both carries information and has properties that permit efficient radar parameter estimation. This work package will examine different potential joint waveform designs with the objective of identifying the most promising candidate for implementation in subsequent work packages. Several different approaches will be considered. One approach is time division, where communication signals are sent for a fraction of time followed by radar signals. The fraction can be adjusted based on situational awareness. For example, in a rural area radar to look for animals may be more important than communication, while in an urban area, communication to see beyond the horizon of several cars may contain more relevant operational information. Other ways of combining radar and communication will be considered including different frequency domain techniques (based for example on orthogonal frequency division multiplexing). Corresponding signal processing algorithms will be developed for the receiver operation as well.

Dependencies: Leverages the mathematical results and insights obtained from Work Package 2.1.1.

Completion criterion: A best waveform for joint communication and radar is identified from among several candidates.

Deliverables: *None.*

Technical Rationale: Radar and communication can be combined together to make better use of common radio resources (in this case bandwidth and time). By tuning key parameters, it will be possible to select a common waveform that provides the right compromise between multiple objectives.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 2.1. The assigned budget for this work package is $54,160.

Test and Demonstration Plan: There will be no formal testing or demonstration.

Subtask 2.2 Optimizing the joint waveform to meet different objectives

Duration: Months 7-10

Overall Description: Wireless communication systems have limited resources (bandwidth and power). How these resources are allocated among communication and radar will depend on the situation. This subtask of the research is focused on optimizing parameters to meet different performance objectives.

Detailed Description: As indicated earlier, optimizing parameters is an important part of having a timely and meaningful wireless system for transportation safety purposes. For instance, consider the extreme case of a rural setting. In this situation, there are few vehicles around therefore the majority of system resources might be devoted to radar to look for pedestrians, bicycles, or animals. Another extreme case is gridlock in an urban area. In this case, more information may perhaps be derived from communication through other vehicles to understand the situation several car lengths ahead, therefore more resources devoted to communication. The optimization will have to be dynamic based on vehicular and communication traffic. For example, if many vehicles have communication and radar capability, their signals may create interference [SW11] [SSR+11]. This means that additional considerations are needed to provide both communication and radar efficiency. For example, resources might have to be shared among different neighboring vehicles in a distributed fashion. Such functions are common in wireless communications (a key role of the medium access control protocol) but have never been developed for a waveform that also includes radar.

Dependencies: This subtask is closely intertwined with Subtask 2.1, and is a successor to that task once a framework has been developed in Subtask 2.1 to combine joint millimeter wave communications and radar.

Completion criterion: This subtask will be complete when the research team has developed high-level optimization protocols customized to different traffic conditions and different location-specific characteristics.

Deliverables: None.

Technical Rationale: This subtask optimizes resources, so that they are used most effectively depending on traffic conditions and locational attributes. Doing so will enable a better distributed processing capability for CA/CW systems.

Basis of Estimate: This subtask will constitute 20% of the effort and resources corresponding to Task 2. The assigned budget for this subtask (including all work packages) is $54,160.

Test and Demonstration Plan: This subtask will involve some basic testing for functionality and optimization, though some preliminary testing will be undertaken later in Task 3.

<u>Work Package 2.2.1: Definition of the different working scenarios.</u>

Duration: Month 7

General Description: The objective of this work package is to identify different transportation working scenarios that will be used for subsequent performance evaluations.

Detailed Description: The performance requirements for CW/CA depend on the different operational scenarios. Different working scenarios will introduce different challenges that must be addressed. For the purposes of this work package is to identify certain working scenarios that can be used to benchmark different algorithms. Example scenarios might be detecting the presence of a bicycle near a car, a bicycle several cars ahead, avoiding collision with a pedestrian, or identifying an open car door. Each of these scenarios will have a different optimal mixture of communication from other cars and detection of the local environment through radar.

Dependencies: Depends on the development in Subtasks 1.1, 1.2, and 2.1.

Completion criterion: The work package will be complete when three or more working scenarios are identified with enough parameterization to permit simulation of different algorithms.

Deliverables: No specific deliverable.

Technical Rationale: Radar and communication each solve different problems. Radar excels at identifying the local area around the vehicle with potentially very low latency and high precision. Communication has the advantage of being able to convey information from sensors in other cars that may be hundreds of feet away. Identifying different scenarios is important for developing algorithms that work across a variety of possible circumstances.

Basis of Estimate: This work package will constitute 20% of the effort and resources corresponding to Subtask 2.2. The assigned budget for this work package is $10,832.

Test and Demonstration Plan: None.

<u>Work Package 2.2.2: Designing optimization strategies.</u>

Duration: Months 8-10

General Description: Optimization is the general technique that involves selecting the best choice of parameters for a given cost function. In this work package, optimization strategies are proposed and solved to achieve good joint communication and radar performance across the scenarios identified in Work Package 2.2.1.

Detailed Description: In Subtask 2.1, a joint framework for mmWave communication and radar will be developed. In that framework, there will be various parameters that need to be adjusted to achieve the best performance. The objective of this work package is to identify specific algorithms that can be used to select a good choice of parameters, based on the scenarios identified in Work Package 2.2.1. To avoid mathematical technicalities that are often associated with optimizations, it is likely that the parameter space will be discretized and only a finite set of combinations will be evaluated based on a weighted cost function derived from radar and communication performance metrics. Specific metrics of performance in the CW/CA application include the probability of detection of a collision (ideally very high) and the probability of a miss (where a collision is not detected) and the probability of a false alarm (where a collision is detected incorrectly). Communication can be used to help in the collision detection, and may also form an additional constraint in the optimization, e.g. radar is performed subject to a certain minimum communication throughput required.

Dependencies: Depends on the working scenarios from Work Package 2.2.1, and the framework from Subtask 2.1.

Completion criterion: Success occurs if a suitable cost function and set of constraints are defined that can be subsequently used to optimize the joint communication and radar waveform.

Deliverables: None.

Technical Rationale: Adapting the parameters of the joint communication and radar waveform is expected to be very challenging given multiple performance objectives and constraints. Consequently, mathematical tools will be needed to formulate and solve these problems with low complexity.

Basis of Estimate: This work package will constitute 80% of the effort and resources corresponding to Subtask 2.2. The assigned budget for this work package is $43,328.

Test and Demonstration Plan: None in this work package, other than some basic testing for functionality. Preliminary testing of the strategies will be undertaken in Task 3 as possible given the data readily available or collectible.

Subtask 2.3. Incorporating antenna arrays

Duration: Months 8-10

Overall Description: Antenna arrays are important in millimeter wave communication systems. They allow the transmitter and receiver to form sharp beams with high gain. This is useful in providing higher throughput and lower interference in communication, and also aids in determining position in radar. Antenna arrays are widely considered in millimeter wave communication systems [PCPY10] but are only one of many options in radar [HTS+12]. This subtask of the research will develop algorithms for antenna arrays for joint communication and radar performance.

Detailed Description: There are many tradeoffs to be made in antenna arrays development. For example a vehicle may point its beam to another vehicle to communicate more data, but scanning that beam around may lead to better detection about the environment. Another important tradeoff will be between power consumption and performance. As shown in our prior work [AALHJ14] [AEALH13], the use of a mixture of analog and digital beamforming can dramatically reduce the power consumption associated with beamforming in the communications application, but this has not been explored for radar. The use of antenna arrays will be vital to the success of joint automotive radar and communication.

Dependencies: Depends on results from Subtasks 2.1. and 2.2.

Completion criterion: This subtask will be complete when the research team has developed algorithms for incorporating antenna arrays within joint automotive radar and communications.

Deliverables: None.

Technical Rationale: This subtask focuses on tradeoffs in antenna arrays design and development, which is important in millimeter wave communication systems.

Basis of Estimate: This subtask will constitute 20% of the effort and resources corresponding to Task 2. The assigned budget for this subtask (including all work packages) is $54,160.

Test and Demonstration Plan: This subtask will involve some basic testing for trade-off analysis in antenna array design. Preliminary testing will be undertaken in Task 3 as possible based on data availability.

<u>Work Package 2.3.1: Designing antenna array structures for joint radar communication units at mmWave.</u>

Duration: Months 8-10

General Description: Antenna arrays are an important component of millimeter wave communication systems. This work package considers the role that antenna arrays might play in the combined communication and radar design problem.

Detailed Description: Millimeter wave communication systems use high gain antennas to increase the received signal aperature, and therefore the received signal power. The most flexible way to create high gain antennas with adaptive patterns is through the use of antenna arrays, where multiple antenna elements are controlled together to create one large adaptive antenna. Antenna arrays can be used to form directive beams, reduce mutual interference among neighboring communication links, and support communication with multiple devices simultaneously. In a radar system, antenna arrays can be used to steer a beam to give information about azimuth and elevation of a given target. There is a tension between pointing the beam of the array at a potential target and pointing the beam towards a potential data receiver. This work package will focus on the potential antenna architectures that may be useful for simultaneously performing both communication and radar. Constraints include the area available on the vehicle and the frequency bands of operation.

Dependencies: Leverages results from Subtasks 2.1 and 2.2, and is interrelated with work package 2.3.2.

Completion criterion: Candidate geometries are suggested for antenna arrays operating at mmWave frequencies.

Deliverables: No specific deliverables.

Technical Rationale: Antenna arrays are composed of many antennas. They can be configured in different ways, for example for sharp beams, or to allow beam scanning over a wide area. The performance of the signal processing algorithms depends a great deal on the array manifold through the array geometry.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 2.3. The assigned budget for this work package is $27,080.

Test and Demonstration Plan: None.

<u>Work Package 2.3.2: Designing beamforming algorithms for joint communication and radar performance.</u>

Duration: Months 8-10

General Description: Antenna arrays are used to steer beams at both the transmitter and the receiver. They are an important ingredient in any mmWave communication or radar system. This work package considers the algorithmic implications of using antenna arrays on communication and radar.

Detailed Description: Subtasks 2.1 and 2.2 develop a framework for mmWave communication and radar assuming fixed antennas. MmWave systems can exploit adaptive antennas, where the pattern can be reconfigured very quickly, to become more flexible. This work package will develop algorithms for configuring the antenna arrays for both communication and radar. The choice of algorithms will depend on the available hardware, for example the first Co-PI's previous work considered hybrid beamforming that reduces required hardware complexity at the expense of suboptimal performance [AALHJ14] [AEALH13] [EAHRP13]. This work though was only from a communication perspective and did not consider radar waveforms at all. One interesting direction of work is to use multiple beams to allow both radar and communication to coexist in different angular domains. For example, a beam could be directed at a target communication receiver while another beam is scanning for potential collisions with bicycles and pedestrians. Tradeoffs between communication and radar will be derived based on information in the angular domain, and this information will be used to inform the selection of the best array architectures in work package 2.3.1.

Dependencies: Interrelated with WP 2.3.1. Both are performed at the same time.

Completion criterion: Algorithms are proposed that are able to achieve improved performance over fixed beam algorithms.

Deliverables: None.

Technical Rationale: There are many different ways to use antennas in a communication or radar system. MmWave systems can benefit from adaptively steered beam patterns. Algorithms are needed to adapt the antennas in a way that is meaning for the joint communication and radar application.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 2.3. The assigned budget for this work package is $27,080.

Test and Demonstration Plan: This work package will involve some basic testing for trade-off analysis in antenna array design. Preliminary testing will be undertaken in Task 3 as possible based on data availability.

Subtask 2.4 Dealing with security issues

Duration: Months 8-10

Overall Description: Antenna arrays in millimeter V2V communications include several layers of security and privacy protection, so that the owners of vehicles keep their right to privacy and at the same time a vehicle can rely on safety data sent from other vehicles to take appropriate warning decisions. This subtask will focus on investigating how different and conflicting objectives of security, high throughput, and accurate target detection can be achieved.

Detailed Description: Security is normally implemented in high layer protocols. It is possible, however, to develop special waveforms with enhanced security. Large antenna arrays can be used to provide an extra layer of security [VLHJ13], by making use of excess transmit antennas to help randomize the transmission. This kind of technique provides a low complexity solution that makes it difficult for an eavesdropper to intercept signals from other vehicles or to spoof a vehicle. Security of millimeter wave wireless systems has yet to be studied in detail. Further research is needed to determine under which conditions (array geometry, number of selected antennas, eavesdropper location, etc.) these techniques provides enough security to be relevant to the automotive case. In addition, the combination of security, radar, and communication has yet to be studied. This subtask will investigate alternative configurations to develop a framework protocol to address security issues within the context of the automotive radar and communications.

Dependencies: This subtask builds on earlier subtasks in Task 2.

Completion criterion: This subtask will be complete when the research team has developed some insight into how antenna arrays might be used to enhance security on the communication link.

Deliverables: No specific deliverables will be associated with this subtask.

Technical Rationale: This subtask optimizes resources, so that they are used most effectively depending on traffic conditions and locational attributes. Doing so will enable a better distributed processing capability for CA/CW systems.

Basis of Estimate: This subtask will constitute 20% of the effort and resources corresponding to Task 2. The assigned budget for this subtask (including all work packages) is $54,160.

Test and Demonstration Plan: This subtask will involve some basic testing for functionality and optimization, with additional preliminary testing as possible in Task 3.

Work Package 2.4.1: Using large antenna arrays to provide security at the physical layer.

Duration: Months 8-10

General Description: The goal for this work package is to identify different strategies for randomly switching antenna subsets in a large antenna array. By numerical simulations, the project team will select the technique providing the most appropriate tradeoff between the achieved level of security and the size of the sidelobes.

Detailed Description: The large number of antennas available at mmWave communications motivates the usage of antenna-level modulation techniques, which can introduce randomness at the constellations viewed at angles other than the target directions. This can be achieved by randomly selecting a subset of antennas in the large array for the transmission of every symbol. Many selection strategies are possible, and will have to be designed and analyzed in detail inside tis workpackage. To study the security level that can be achieved by the different strategies, the project team will compare communication metrics of performance like symbol error rate and mutual information in undesired transmit directions associated to the different selection schemes. Side lobes associated to the different antenna subset selection strategies have also to be taken into consideration, since they affect the ability of the transmitting array to communicate with the target receiver. The emphasis of this study will be on understanding how to make the communication link more secure, thus enhancing the overall safety of the system.

Dependencies: Leverages results from Subtask 2.3 and is interrelated with Work Package 2.4.2. Both are performed at the same time.

Completion criterion: Algorithms are proposed that are able to provide some additional security against a sufficiently sensitive eavesdropper.

Deliverables: None.

Technical Rationale: There are many different ways to select an antenna subset randomly for every symbol to be transmitted. Different strategies have to be designed and analyzed, to select the algorithm that provides the best performance.

Basis of Estimate: This work package will constitute 60% of the effort and resources corresponding to Subtask 2.4. The assigned budget for this work package is $32,496.

Test and Demonstration Plan: None.

Work Package 2.4.2: Analysis of the security level in the automotive case.

Duration: Months 9-10

General Description: The objective of this package is to obtain theoretical limits for the security levels that can be achieved by randomly switching antenna subsets in large antenna arrays.

Detailed Description: In addition to mutual information and symbol error rate simulations to be performed in Work Package 2.4.1, it is use to develop mathematical bounds on the achievable security level by antenna subset modulation techniques. Knowledge of these bound allows optimization of the modulation parameters, and shows the maximum security level that could be achieved by the "best" selection technique. It is also necessary to understand the influence of the size of the antenna subset and the array size on the level of achievable security. These bounds will allow the additional dimension of security to augment the developments in Subtask 2.1, which only considers tradeoffs between communication and radar performance. One important question that will be addressed is whether adding additional physical layer security (in the form of randomizing the transmit beams) has an impact on the performance of radar. It is not clear that randomizing the sidelobes will be bad, indeed it could actually be beneficial for the radar system.

Dependencies: Leverages results from Subtask 2.3 and is interrelated with Work Package 2.4.1.

Completion criterion: This work package will be complete when the research team has conducted the analytical study of the security level that can be achieved with different random selections of antenna subsets using operating parameters relevant to the automotive case.

Deliverables: None.

Technical Rationale: This package establishes theoretical limits on the security level that can be achieved by an antenna subset modulation technique. From this information the project team will be able to optimize parameters of the modulation strategies designed in Work Package 2.4.1.

Basis of Estimate: This work package will constitute 40% of the effort and resources corresponding to Subtask 2.4. The assigned budget for this work package is $21,664.

Test and Demonstration Plan: This work package will involve some basic testing. Preliminary testing will be undertaken in Task 3 as possible based on data availability.

Task 3: Conduct Preliminary Tests, Develop Concept of Operations (CONOPS), and Formulate Detailed Plans for Phase II and III Research

Duration: Months 8-12

General Description: This task will undertake some very preliminary tests of the conceptual design and framework developed in earlier tasks, fine-tune algorithms and parameters as appropriate, provide an estimate of the benefits from full development, and identify appropriate directions for subsequent phases.

Detailed Description: The three subtasks in this task assimilate the information from the conceptual development (including an initial identification of the potential "weak" links of the system), obtain a limited amount of real data to test the conceptual and functional design of the proposed CW/CA system, provide a preliminary estimate of the current technology readiness level (TRL) of each component and the overall CA/CW system, and provide estimates of the potential improvements in safety in the real-world through the proposed CA/CW system. These assessments and estimates will serve as the basis for a “go/no go” decision point regarding subsequent funding in Phases II and III. Based on this decision, the third work package will entail the development and specification of full Phase II and Phase III work plans at the subtask and work package levels.

Dependencies: This task relies on all earlier tasks, subtasks, and work packages.

Completion Criteria: When this task is complete, the research team will have an estimate of the benefits from Phase II/III funding, and, as appropriate, a detailed work plan in Phase II, with an overview of the work plan in a potential Phase III.

Deliverables: The preliminary analysis of benefits will be included in the final report. The CONOPS document will form a separate deliverable, to be provided electronically to RTI. Although not a formal deliverable for Phase I, the primary outcome from this task will be a detailed work plan for Phases II and an overview of the work plan for a possible Phase III that will be presented in a new proposal to RTI.

Technical Rationale: The rationale for this task is to assess the potential benefits of the proposed system including weak links for field deployment, and make a determination to move (or not) to additional phases.

Basis of Estimate: The assigned budget for this task (including all subtasks and work packages) is $235,400. This involves $36,203 for professional staff (0.2 months @ $17,187/mo; 0.2 months @ $15,620/mo; 0.2 months @ $18,198/mo; 4.8 months @ $4167/mo; 0.6 months @ $10,000/mo); $38,640 for graduate student assistants (9.6 PhD student-months @ $2075/mo.; 9.6 MS student-months @ $1950/mo.), $4,076 for administrative staff (0.6 months @ $5404/mo. and 0.2 months @ $4167/mo; this is for non-routine duties related to scheduling project-specific meetings, taking meeting minutes and preparing monthly progress reports, and compiling work package and subtask results into the technical memorandum deliverable); $22,886 fringe benefits (29% of labor), $18,267 tuition for the graduate student assistants; $979 for general supplies; $400 for phone and internet; $800 for reproduction costs; $1500 for computer systems support; $1000 for project-related travel, $100,000 for equipment, $10,649 overhead (10% of all expenses excluding tuition and equipment).

Test and Demonstration Plan: This task will be the one that collects some limited amount of data to test the proposed CW/CA system. The testing will be used to revise the proposed design of the CW/CA system as needed and appropriate, and will also serve as a first indication of the potential effectiveness of the proposed system in reducing collisions.

Subtask 3.1: Preliminary tests with real data

Duration: Months 8-10

General Description: The project team will develop a preliminary study to evaluate the performance of a joint radar and communications unit for safety purposes.

Detailed Description: In this subtask, the team will review available V2V and radar hardware for suitability in our collection of real data. Once selected, the team will purchase enough hardware to equip three test vehicles. The test vehicles will be different in body type, to examine the effect of vehicular characteristics on the CA/CW system, and to customize parameters of the system for different types of vehicles. At this time, we propose to use, based on earlier research findings (see, for example, [EBH08], and [NPB13]), three body types that have been shown to be quite different in terms of crash rates and crash consequences: a sedan, a sports utility vehicle, and a van. Different driving scenarios will be identified, and real data will be collected around the prime organization's campus. The collected data will be organized into a test database, which will be used to perform simulations to assess the performance of the overall CA/CW system. Equipment to interface with the radar and communications modules, along with assistance in the use of these modules, will be procured from National Instruments (NI). The entire cost of the equipment and assistance will be $75K. We propose to use three rental vehicles already equipped with the radar modules, and then retrofit communication modules on these three rental vehicles. The cost for this is estimated at $25K.

Dependencies: This subtask is based on the results of all earlier tasks, subtasks and workpackages.

Completion Criteria: Numerical studies that show the performance of the joint radar and communication unit at mmWave frequencies for roadway safety purposes.

Deliverables: None.

Technical Rationale: This subtask focuses on the exhaustive evaluation of the developed software model for a joint radar and communication unit for roadway safety purposes.

Basis of Estimate: This subtask will constitute 40% of the effort and resources corresponding to Task 3. The assigned budget for this subtask (including all work packages) is $154,160 ($100,000 for equipment is included in this subtask, specifically in Work Package 3.1.1).

Test and Demonstration Plan: None

Work Package 3.1.1: Collect real data.

Duration: Month 8

General Description: This work package is devoted to the collection of a set of real data that will be used to test the architectures and algorithms associated to the concept of radar-communicating unit.

Detailed Description: Three test vehicles will be equipped with commercial automotive radar and V2V communications hardware. These vehicles will collect real data in different driving scenarios around the prime organization's campus. A complete test database will be generated and used in subsequent work packages to test the concepts developed in Subtasks 1.1 and 1.2. A complete database documentation has to be developed as well.

Dependencies: Test database generated in this work package will be used in Work Package 3.1.2.

Completion criterion: Test database and corresponding documentation are created.

Deliverables: None.

Technical Rationale: This work package focuses on the development of a test data, stored in a database that will be used in preliminary tests.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 3.1. The assigned budget for this work package is $27,080, plus $100,000 for equipment ($127,080 total).

Test and Demonstration Plan: None.

Work Package 3.1.2: Simulation results using real data.

Duration: Months 9-10

General Description: The goal of this work package is to obtain preliminary results on the performance of the architecture and corresponding algorithms for integrated radar and communication as developed in Task 1.

Detailed Description: This work package will include the evaluation of the performance of the concepts and test algorithms using a limited amount of real data. A software model will be developed for each system component and the CA/CW system as a whole. Exhaustive numerical simulations using real data collected in Work Package 3.1.1 will be performed for the different driving scenarios. From the results of these simulations the project team will extract preliminary conclusions about the performance of the systems designed in Task 1.

Dependencies: Depends on results from Subtask 1.2 and database generated in Work Package 3.2.1.

Completion criterion: This work package will be complete when the research team has performed all the necessary simulations to assess the performance of the algorithms developed in Task 1.

Deliverables: None.

Technical Rationale: Many of the proposed algorithms are data driven, meaning that real data can be included to improve their operation. New simulations are needed after updating the models to determine how the data has improved their operation.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 3.1. The assigned budget for this work package is $27,080.

Test and Demonstration Plan: This task involves testing using real input data.

Subtask 3.2: Assess benefits of proposed system and develop CONOPS

Duration: Months 9-12

General Description: This subtask will synthesize the information from the preliminary test results in Task 3.1 and provide an estimate of the current technology readiness level (TRL) of each component and the overall CA/CW system

Detailed Description: The subtask will identify the “weak” links of the system based on the limited results from Subtask 3.1, and redesign the system as feasible and appropriate. If unable to redesign due to time constraints, these “weak” links will be noted and carried forward to Phase II efforts to isolate problems and improve performance. This work package will also provide estimates of the potential improvements in safety in the real-world through the proposed CA/CW system.

Dependencies: This subtask is based on all earlier tasks, subtasks, and work packages.

Completion Criteria: The subtask is complete when the research team has assessed the potential benefits of the system in terms of roadway safety, as well as developed a full CONOPS.

Deliverables: A separate stand-alone CONOPS document.

Technical Rationale: As required by TxDOT.

Basis of Estimate: This subtask will constitute 50% of the effort and resources corresponding to Task 3. The assigned budget for this subtask (including all work packages) is $67,700.

Test and Demonstration Plan: None.

<u>Work Package 3.2.1: Assess benefits of proposed system.</u>

Duration: Months 9-11

General Description: This work package will evaluate the benefits of the proposed system based on initial results and simulations. Metrics of performance will be used to determine the performance of the proposed algorithms and their potential impact on transportation safety.

Detailed Description: The work package will use the results and simulations from the earlier subtask to provide a holistic evaluation of the proposed framework and algorithms. A main objective will be to quantify performance in different settings and then to relate this performance to human-centric transportation safety metrics. The human element is critical in understanding the efficacy of the system. For example determining the relative importance of a collision false alarm (no actual collision is eminent) or a missed collision will be critical for people to develop trust in the system. This work package will also identify the "weak" links in the system, to the extent that they can be identified from the limited testing in the previous subtask. The "weak" links will be identified and solved if possible, otherwise they will be forwarded for further study in the Phase II effort. A final objective will be to provide real-world estimates of the potential for improvements in safety in real-world environments, quantified in terms loss of human life and property damage, especially in incidents involving non-vehicular collisions with pedestrians or bicycles. This will show how the proposed framework can be effective if deployed on a larger scale.

Dependencies: This work package is based on all earlier tasks, subtasks, and work packages.

Completion criterion: The work package is complete when the research team has assessed the potential benefits of the system in terms of roadway safety.

Deliverables: None.

Technical Rationale: The proposed system is complicated with many different adaptable features. A holistic evaluation is required to assess performance in terms of safety.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 3.2. The assigned budget for this work package is $33,850.

Test and Demonstration Plan: The benefits of the proposed system will be demonstrated.

Work Package 3.2.2: Develop CONOPS.

Duration: Months 11-12

General Description: This work package will develop a full CONOPS document for the proposed collision avoidance system.

Detailed Description: This work package will develop a CONOPS for the proposed system. The purpose of the document will be to communicate the overall system characteristics to end-users, auto manufacturers, suppliers, TxDOT, and cities, from an integrated systems point-of-view. The document will summarize the operation of the integrated communication and radar system, as well as the joint mmWave communication and radar system. It will explain the key software and hardware components of each of these systems and will explain how the entire system, including vehicles with and without communication capability, interacts.

Dependencies: This work package is based on all earlier tasks, subtasks, and work packages.

Completion criterion: When the team has developed and delivered a CONOPs document.

Deliverables: CONOPS document.

Technical Rationale: As required by TxDOT and for possible future phases.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 3.2. The assigned budget for this work package is $33,850.

Test and Demonstration Plan: None.

Subtask 3.3: Develop detailed Phase II and Phase III work plans

Duration: Month 12

General Description: The research team will develop full Phase II and III work plans based on Phase I results.

Detailed Description: Based on research conducted in Phase I, the research team will identify weak links for further exploration in Phase II and Phase III, as well as identify specific improvements that may be made in the algorithms and in system integration. This decision will be informed by the quantification of benefits Work Package 3.2.1. The research team's preliminary vision for these phases, along with cost estimates and schedule, is outlined in the "Preliminary Phase II and III Plans," located above in the Work Plan. This vision will be modified as necessary based on Phase I results, and presented to RTI in the form of a new proposal. The proposal may be modified based on discussions with TxDOT until the end of the Phase I project.

Dependencies: This work package is interrelated with the quantification of benefits in Work Package 3.2.1.

Completion Criteria: This subtask is complete with the submission of a proposal for Phase II and the further development of Phase III.

Deliverables: None.

Technical Rationale: The preliminary vision for Phase II and Phase III research has been proposed based on the anticipated successes in Phase I. Once the research, simulations, and initial validation is complete, however, it is expected that the more promising areas of further inquiry will be identified.

Basis of Estimate: This subtask will constitute 10% of the effort and resources corresponding to Task 3. The assigned budget for this subtask (including all work packages) is $13,540.

Test and Demonstration Plan: None.

<u>Work Package 3.3.1: Detailed plan for Phase II.</u>

Duration: Month 12

General Description: The research in Phase II is focused on prototyping efforts that will be used for more extensive data collection, algorithmic demonstration, and proof-of-concept demonstrations. This phase will include the design of a test-bed and associated experiments to demonstrate concepts, test components, and mitigate risks.

Detailed Description: The emphasis of Phase II will be placed on further development of the prototype for both integrating communications and radar as well as the development of new prototyping capabilities for joint mmWave radar and communication. Each system component and the CA/CW system as a whole will be prototyped, along with designing a virtual transportation system test-bed for functionality testing. This phase will include an experimental design to test scalability effects even if only within the parameters allowed by the testbed. The experiments will identify which parts of the system need further improvement and will identify ways to reduce risk. At the end, requirements for full deployment will be developed, including providing an estimate of the current technology readiness level (TRL) of each system component will be put together.

Dependencies: Depends on the outcomes of Tasks 1.1 and 1.2

Completion criterion: A final proposal is submitted for Phase II.

Deliverables: None.

Technical Rationale: Much of Subtasks 1.1 and 1.2 are focused on the theory of integrating communication and radar, along with designing joint communication and radar at mmWave frequencies. Initial data will be collected to validate the research ideas but more extensive data collection (which may take many months is deferred to Phase II). The results from Phase II will be used to further refine the results from Phase I.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 3.3. The assigned budget for this work package is $6,770.

Test and Demonstration Plan: None.

<u>Work Package 3.3.2: Detailed plan for Phase III.</u>

Duration: Month 12

General Description: The research in Phase III is focused on larger scale field tests of the developed communication and radar systems. This will provide practical demonstrations of these strategies for a variety of roadway geometrics, roadway control systems, environmental conditions, and driver characteristics. Unlike the tests undertaken earlier, these field tests will be based on regular travel conditions in different parts of Austin, and will be undertaken with the help of TxDOT and the Department of Public Safety.

Detailed Description: Phase III will involve large scale field tests and further refinement of the proposed framework. This will involve several subtasks where experiments are performed over a variety of different environments and conditions to determine both the efficiency of the current framework and the robustness of the proposed algorithms. The results will be used for subsequent further refinement of the proposed framework and algorithms. For example, the additional data can be used by the machine learning algorithms to better classify different operational scenarios (e.g., collision eminent, pedestrian present, etc) or can be used in the joint communication radar waveform optimization to better adapt based on the probability of different scenarios occurring. The final major task of Phase III will involve technology transfer, including meetings with TxDOT and stakeholders to discuss the framework and project findings, and develop implementation strategies to facilitate deployment as soon as possible following conclusion of the project

Dependencies: Depends on the outcomes of Subtasks 1.1 and 1.2.

Completion criterion: A plan of action and preliminary proposal for Phase III is developed.

Deliverables: None.

Technical Rationale: The data collection in Phase II will be more extensive than Phase I, but will still consider a smaller scale with the main objective of further improving the proposed algorithms. Phase III will perform more extensive large-scale tests of the algorithms, with the objective of understanding how they perform in a variety of different practical environments.

Basis of Estimate: This work package will constitute 50% of the effort and resources corresponding to Subtask 3.3. The assigned budget for this work package is $6,770.

Test and Demonstration Plan: None.

4. IDENTIFICATION OF INFORMATION TECHNOLOGY (IT) DELIVERABLES TO TXDOT

None.

5. ASSISTANCE OR INVOLVEMENT BY TXDOT

The research team will meet with key TxDOT roadway safety personnel at regular intervals to obtain their input and ensure that the project is grounded in potential applicability in future phases. Such discussions also will provide the research team with the opportunity to work with the TxDOT in a cooperative process to guide the project. The assistance of TxDOT will be sought specifically in Work Package 3.1.2 (that is, the design of the test-bed experiments), and in Work Package 3.3.2 (development of Phase II and Phase III plans).

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Form DelTable
(Rev. 5/2013)
(RTI)

Deliverables Table
Project No. 15-1

Note: Deliverables on this Table are not considered accepted by TxDOT until formal notice is provided by the RTI Project Manager. All written deliverables should be submitted to RTIMain@txdot.gov. For instructions of submission procedures for other formats, see chapter 7 of RTI's *University Handbook.* **The Research Supervisor is ultimately responsible to TxDOT for all deliverables, no matter what agency is assigned as the primary developer. However, the primary developer should be listed under the column "Primary Agency" for each deliverable.**

Status Reports: The research supervisor must submit written progress reports at least monthly outlining work and staff utilization. Reports should be submitted to the project manager no later than the 3rd day of the following month (July 3 for the June status, August 3 for July status, etc.).

Technical Memoranda: A technical memorandum documenting work completed for each task shall be listed on this table as deliverables. **Each technical memorandum shall be due within 15 days after the end of the task as defined in the Project Schedule.**

Deliverables: Deliverables will be as specified on the **Project Statement** (Research Project) or **IPR** (Implementation Project). Examples of products typically most appropriate as stand-alone items include Guidebooks, Training Materials, Devices, Instruction Manuals, Brochures, and Software.

No.	Deliverable Description	Due Date (before project termination)	Primary Agency	Comments
R1	Research Report	10/31/2015	CTR	A fully edited report is due on or before the last day of the contract. The report should be complete and all information correct and include tables, graphs, and illustrations. The final draft does not have to incorporate layout/design work required for publication.
PSR	Summary of work performed, findings and recommendations	10/31/2015	CTR	
TM-1	Technical Memorandum for Task 1	8/31/2015	CTR	
TM-2	Technical Memorandum for Task 2	8/31/2015	CTR	
TM-3	Technical Memorandum for Task 3	10/31/2015	CTR	

Revision Number:

Date Updated:

Schedule of Research Activities

Form Schedule
(Rev. 5/2013)
(RTI)

	Original Schedule
	Work Completed
RRRRR	Revised Schedule

Created Date: August 28, 2014

Note: Each task must produce one or more deliverables. All deliverables should be submitted to RTIMain@txdot.gov.

	Research Activity	Estimated Cost of Task	FY 2015												FY 2016												FY 2017											
			Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug
Task 1	**Conceptual and Functional Framework for Integrating Communications and Radar**	**$270,800**																																				
Subtask 1.1	Develop improved collision detection and avoidance algorithms for cars	$108,320																																				
Work Package 1.1.1	*Combining information from the communication and radar systems*	*$54,160*																																				
Work Package 1.1.2	*Incorporating vehicular dynamics and driver behavior*	*$54,160*																																				
Subtask 1.2	Develop improved collision detection and avoidance algorithms between cars and non-motorized road users (bicycles and pedestrians)	$81,240																																				
Work Package 1.2.1	*Incorporating radar signals to computer vision oriented methods for pedestrian and bicycles detection*	*$40,620*																																				
Work Package 1.2.2	*Designing a V2V communication strategy to improve CW/CA algorithms*	*$40,620*																																				
Subtask 1.3	Dealing with uncertainty (caused, for example, by delays in the communication and inconsistency in data sources) and harnessing the power of collective intelligence	$81,240																																				
Work Package 1.3.1	*Developing statistical models for the different types of uncertainty*	*$24,372*																																				
Work Package 1.3.2	*Introducing reliability and availability of data into the decision making process*	*$24,372*																																				
Work Package 1.3.3	*Collective intelligence: A principled framework for distributed decision making*	*$32,496*																																				
Monthy Progress Reports					x	x	x	x	x	x	x	x	x	x																								

Revision History:

Schedule of Research Activities

Form Schedule
(Rev. 5/2013)
(RTI)

Legend	
	Original Schedule
	Work Completed
RRRRR	Revised Schedule

Created Date:

Note: Each task must produce one or more deliverables. All deliverables should be submitted to RTIMain@txdot.gov.

			FY 2015												FY 2016												FY 2017											
	Research Activity	Estimated Cost of Task	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug
Task 2	**Developing Joint Automotive Radar and Communication at the mmWave Band**	**$270,800**																																				
Subtask 2.1	Develop a framework for joint millimeter wave communication and radar	$108,320																																				
Work Package 2.1.1	*Studying the tradeoffs between radar and communication*	*$54,160*																																				
Work Package 2.1.2	*Designing joint waveforms and signal processing algorithms*	*$54,160*																																				
Subtask 2.2	Optimizing the joint waveform to meet different objectives	$54,160																																				
Work Package 2.2.1	*Definition of the different working scenarios*	*$10,832*																																				
Work Package 2.2.2	*Designing optimization strategies*	*$43,328*																																				
Subtask 2.3	Incorporating antenna arrays	$54,160																																				
Work Package 2.3.1	*Designing antenna array structures for joint radar communication units at mmWave*	*$27,080*																																				
Work Package 2.3.2	*Designing beamforming algorithms for joint communication and radar performance*	*$27,080*																																				
Subtask 2.4	Dealing with security issues	$54,160																																				
Work Package 2.4.1	*Using large antenna arrays to provide security at the physical layer*	*$32,496*																																				
Work Package 2.4.2	*Analysis of the security level in the automotive case*	*$21,664*																																				
Monthy Progress Reports					x	x	x	x	x	x	x	x	x	x																								

Revision History:

Schedule of Research Activities

	Original Schedule
	Work Completed
RRRRR	Revised Schedule

Created Date:

Note: Each task must produce one or more deliverables. All deliverables should be submitted to RTIMain@txdot.gov.

	Research Activity	Estimated Cost of Task	FY 2015												FY 2016												FY 2017											
			Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug
Task 3	**Conduct Preliminary Tests, Develop Concept of Operations (CONOPS), and Formulate Detailed Plans for Phase II and III Research**	**$235,400**																																				
Subtask 3.1	Preliminary tests with real data	$154,160																																				
Work Package 3.1.1	*Collect real data*	*$127,080*																																				
Work Package 3.1.2	*Simulation results using real data*	*$27,080*																																				
Subtask 3.2	Assess benefits of proposed system and develop CONOPS	$67,700																																				
Work Package 3.2.1	*Assess benefits of proposed system*	*$33,850*																																				
Work Package 3.2.2	*Develop CONOPS*	*$33,850*																																				
Subtask 3.3	Develop detailed Phase II and Phase III work plans	$13,540																																				
Work Package 3.3.1	*Detailed plan for Phase II*	*$6,770*																																				
Work Package 3.3.2	*Detailed plan for Phase III*	*$6,770*																																				
	Monthy Progress Reports												x	x	x	x																						
	Total (should = 100% of total budget)	**$777,000**																																				

Revision History:

BACKGROUND AND SIGNIFICANCE OF WORK

The quality of the surface Transportation system in Texas urban and rural regions, and in our State as a whole, is intricately linked with economic competitiveness and vitality, and directly impacts the livability of Texas communities at the local level. One particular aspect of the Texas transportation system that is particularly important in this regard is safety. Safety refers to designing transportation systems to minimize loss of human life and reduce property damage attributable to transportation, whether it be on the state's highways or by rail or by other transportation modes. Safety is particularly important at a time when increasing populations in metropolitan areas in Texas, combined with increasing urbanization, is leading to high levels of traffic congestion in Texas cities, as shown in Table 1 [SEL12]. A high level of congestion results in (a) more conflict points on the system as well as potentially aggressive behavior, leading to a degradation in safety, and (b) lower reliability on the system as small perturbations in the system (such as incidents) can get amplified and cause unexpected large-scale and network-wide "collapses", leading to more exposure and thus potentially more crashes.

Table 1: Congestion trends in Texas urban areas.

City	Yearly Hours of Delay per Auto Commuter					Long Term Change (hours)
	1982	2000	2005	2010	2011	1982-2011
Dallas-Fort Worth-Arlington	7	39	50	44	45	38
Houston	51	40	49	51	52	22
Austin	10	40	58	43	44	34
San Antonio	5	37	41	37	38	33
El Paso	4	30	42	31	32	28
McAllen	4	23	27	27	28	24
Brownsville	2	13	16	25	25	23
Beaumont	6	20	29	25	25	19
Corpus Christi	7	12	15	14	14	7

Improvements in safety may be achieved in many ways, including adding capacity (such as building more roads with geometric features that reduce safety hazards), managing vehicle demand (such as congestion pricing and high-occupancy vehicle use incentives to reduce travel exposure), influencing person-travel patterns by reducing travel exposure or spatially/temporally shifting commuters' travel (such as teleworking strategies, work-staggering strategies, flexible work hours, and improved spatial balancing of jobs and housing), and improving operational efficiency of the transportation system (such as ramp metering, signal coordination, quick incident detection and response, and wireless technology that allows vehicles to communicate with one another, with other road users, and with the infrastructure to minimize conflict points and prevent crashes) (see [BBSB14]) . While all of these strategies remain viable and may be appropriate in specific contexts, the first strategy of adding capacity is becoming increasingly infeasible in the financial, land-constrained, and environmental-conscious climate today. Indeed, it is becoming increasingly clear in the profession that we cannot simply build our way out of traffic congestion, especially with the rapid urbanization of Texas cities and the projected population growth in already established Texas urban areas (see Figure 1) [TIF08]. The second and third strategies, which involve demand management, have been considered much more proactively in the past decade or so, though they can be politically sensitive. The fourth strategy is appealing from a financial investment perspective. It entails increasing the safety levels of the current infrastructure, and is also relatively benign and non-controversial from a political/environmental sensitivity perspective.

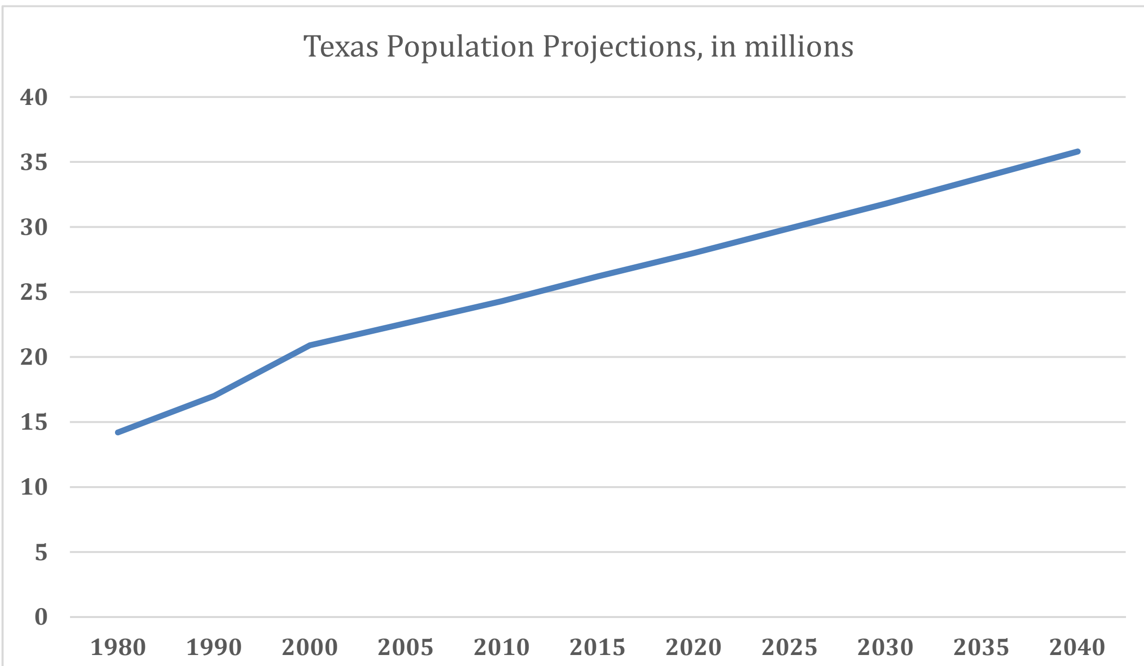

Figure 1: Texas Population Growths, 1980-2040

In the context of improving the operational efficiency of the transportation system, innovations in sensors, cameras, computers, and wireless technologies now make it possible to gather real-time data that have never before been accessible to transportation professionals, as well as to monitor infrastructure systems in an automated and continuous fashion to ensure that they are in good functioning condition and avoid movement conflicts among different transportation system users (including motorists, pedestrians, and bicyclists). In this context, the rapid developments in wireless technology have revolutionized the centralized communication and processing protocol in place in the transportation field for so long, by potentially being able to localize information and process data in a distributed fashion within the wireless network itself (or an "in-network computation") to extract information for improving transportation system safety in near real time. A simple example of this would be collision avoidance systems at a specific intersection or on a specific segment of a freeway through localized in-network computations and the use of control/warning mechanisms using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Furthermore, wireless networks and devices are increasingly found everywhere, thus providing low-cost and system-wide coverage to collect field data.

Two main applications of wireless technologies are communication and radar. Communication is used in V2V and V2I systems [PLFE+09] [SK08] and refers to an exchange of information using radio frequencies. V2V systems rely on a collaborative approach with each vehicle with the possibility of relaying messages through multiple hops, so as to expand the time horizon of information relevant to driving safety, comfort and transportation efficiency. V2V systems satisfy the communication needs of a large class of applications, such as public safety (collision warning), traffic management (emergency vehicles notification), traffic coordination and assistance (platooning, passing and lane change assistance) and comfort (targeted vehicular communication) applications. Today, there are several communication standards that may be used as access networks for V2V communication, such as Bluetooth, IEEE 802.11, and cellular mobile networks [WTM09] [SK08]. The prominent wireless data link for dedicated short-range communications (DSRC) is a variant of IEEE 802.11, denoted as IEEE 802.11p in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz). This protocol specifies the physical and medium access control layers for highly volatile vehicular environment. IEEE 1609.4 specifies the operation of upper layers across multiple channels over the 5.9 GHz band. These two elements, combined with a resource manager for the on-board equipment, and specifications of addressing, networking, and security services, are collectively known as Wireless Access in Vehicular Environment (WAVE) standard, as shown in Fig. 2. Several manufacturers such as AutoTalk, Unex, Denso and Marben, provide commercial V2X communications modules that implement this standard.

Despite the potential of wireless communications technology (or simply communications from hereon) to revolutionize transportation network operation, design, and safety, communications alone has only limited value from a safety enhancement perspective. In particular, communications alone can have high latency (due to complications and time delays in the processing needed to discern a safety hazard), which can lead to the inability to avert a safety problem in time. Also, communications alone does not help much when a vehicle or a road user does not have the technology for V2V or V2I talk (such as would be in the case of an emerging conflict point of a communications-enabled vehicle with a non-communications enabled vehicle or a pedestrian/bicyclist). In this and other cases, radar technology, which predates communications technology and operates in a much simpler conceptual fashion, has the potential to be combined with communications technology to enhance the accuracy and the latency of system, offering superior safety capabilities than communications or radar technology alone.[1]

[1] Radar predates the other applications of wireless in vehicles by a number of years (microwave companies and car manufacturers started joint experiments on vehicular radar in the early 1970s [MD13], while the earliest research in vehicular communications technologies was conducted by the Japan Automobile Research Institute in the early 1980s [Tsu]). Commercial radar products have been available in vehicles for

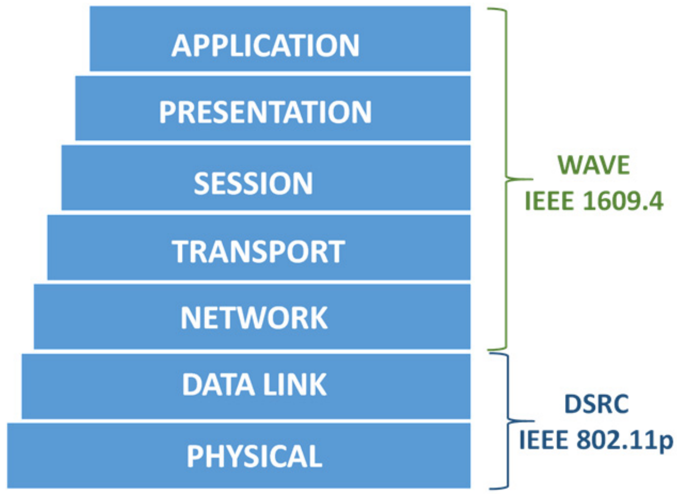

Figure 2: Standards for Wireless Communications in Vehicular Environments

The idea of radar is to send a pulse or waveform from a vehicle, listen to the reflection, and then make inferences about the source of that reflection. For example, a reflection from another vehicle could be used to infer its distance, velocity, and trajectory. Radar is already widely deployed in a large number of vehicles [MD13] [Wen] [car], as shown in Table 1. The automotive radar sensor suppliers are TRW, DENSO, Continental, Hitachi, Bosch, Delphi, Fujitsu Ten and Mitsubishi Electric [car]- They provide different types of automotive radar as shown in Table 2. Automotive radar is being further developed by Infineon, IHP, Fujitsu Ten, Hitachi and Autocruise (TRW). In all 27 member States of the European Union, as well as in all the other countries that are members of the European Conference of Postal and Telecommunications Administrations (CEPT), the use of automotive radars is regulated by ETSI standards, EN 301 091-1 & EN 301 091-2 for 77 GHz Long Range Radar (LRR) and EN 302 264-1 & EN 302 264-2 for 79 GHz Short Range Radar (SRR) [ETS11] [ETS09] [CPA]. In USA, Federal Communications Commission (FCC) has frequency standard FCC 15.253 for 77 GHz LRR and FCC 15.245, 15.249 for 24 GHz SRR [Kom11]. Radar has many applications for both comfort and safety. A main advantage of radar is its ability to make inferences about non-vehicular sources of traffic such as bicycles and pedestrians who may not be equipped with compatible communication technology.

more than fifteen years while communication technology has been limited to telematics applications (e.g. the OnStar system, which does not impact the control of the vehicle).

Table 2: Different car manufacturers including radar equipment and corresponding sensor supplier.

Manufacturer/ type	Sensor Suppliers
BMW 750i	Conti
Mercedes C 350 CDI	Conti
Volvo V40 T4 Summum	Delphi
VW Touareg V8 TDI	Autocruise
Audi A6 3.0 D Quattro	Bosch
Lexus GS 250 F Sport	Denso
Opel Insignia 2.0 BiTurbo CDTI Sport	Delphi
Honda Civic 2.2 i-DTEC Executive	Elesys
Mercedes B 180	Autoliv
Ford Focus 1.6 I EcoBoost Titanium	Delphi
Chrysler Group LLC Vehicles (e.g. Chrysler 300)	Bosch
Mazda 6	Denso

Table 3: Different types of automotive radar provided by several sensor suppliers.

Sensor Suppliers	Types of Automotive Radar
Delphi	Electronically scanning radar: multi-mode, multi-application capability: Simultaneous long- and mid-range functionality
Bosch	Long range radar (dielectric lens antenna)
	Mid range radar
Fujitsu	3D-scan mmWave radar
TRW Autocruise AC20	Monopulse (lens antenna)
DENSO	Electronically scanning antenna array

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Texas Department of Transportation

Research Staff and Facilities

RFP: **15-1** **Date:** **August 28, 2014**

Research Agency(s): **UT/CTR**

1. Research Supervisor's Experience

Dr. Chandra R. Bhat, P.E.
Director, Center for Transportation Research
University Distinguished Teaching Professor
Adnan Abou-Ayyash Centennial Professor in Transportation Engineering
Phone: 512-471-4535, Email: bhat@mail.utexas.edu

The Research Supervisor, ***Dr. Chandra Bhat***, is a Professor of Civil Engineering and is recognized internationally and nationally as a leading expert and pioneer in the area of travel behavior and safety analysis. He is the most cited researcher in the transportation field today, at least based on those registered with the Google Scholar database, and all of Dr. Bhat's publications are in the field of transportation and safety analysis. He was the Chair of the National Transportation Research Board (TRB) committee on Transportation Demand Forecasting, and the President of the International Association for Travel Behavior Research. In the specific context of the current project, Dr. Bhat has been at the forefront of efforts to examine the safety and planning implications of connected and automated vehicles. His leadership in this area has been well recognized. He was invited to provide a keynote lecture on safety considerations and infrastructure needs of connected and automated vehicles at the First Florida Automated Vehicles Summit (see http://www.caee.utexas.edu/prof/bhat/RESEARCH/AV/floridaautomatedvehiclessummitfinal.pdf). He was asked to make a video for South by Southwest (SXSW) discussing the safety, energy, and emissions considerations associated with automated vehicles issues (http://panelpicker.sxsw.com/vote/21547), and was interviewed by KUT Radio on the same topic (https://soundcloud.com/kutnews/how-driverless-cars-could). His presentation on the topic at SXSW (see http://www.caee.utexas.edu/prof/bhat/RESEARCH/AV/sxswpresentationfina.pptx) drew many industry and public policy leaders, with whom he has developed a close professional relationship. Just this summer, he co-chaired a national level team of academics, DOT and metropolitan planning organization (MPO) practitioners, and industry leaders to organize a workshop entitled "Regional Planning and Modeling Implications of Driverless Cars" at the 2014 Automated Vehicles Symposium held in San Francisco. He has been widely cited in the media on the topic of this project statement. Please see http://www.caee.utexas.edu/prof/bhat/RESEARCH/Autonomous.html for a full listing of his technical contributions and media citations directly related to this project.

More generally, Dr. Bhat has worked with the US Department of Transportation, state DOTs, Metropolitan Planning Organizations (MPOs), and consulting agencies to develop innovative planning methods, and data collection and analysis methods, to analyze the implications of a range of infrastructure, technology, and traffic congestion reduction policies for urban and intercity travel. He is a pioneer in policy-sensitive modeling tools, and is world renowned for his planning/modeling system called CEMDAP (Comprehensive Econometric Microsimulator for Daily Activity-travel patterns), which is now fully implemented for the Southern California Association of Governments (SCAG), one of the largest regions in the US encompassing a population of nearly 20 million people. This tool has been used in the past to examine the spatial-temporal patterns of human behavior, as well as the emissions and energy use impacts of improved technology. He has been at the forefront of research on technology adoption behavior, including the purchase of cars (by households) with different driving features, fuel technology, and safety features. A recent paper, entitled "Consumer Preferences and Willingness to Pay for Advanced Vehicle Technology Options and Fuel Types," with his students and other colleagues (see http://www.caee.utexas.edu/prof/bhat/ABSTRACTS/ConsumerPreferenceSmartCars.pdf) is the first of its kind that starts to address issues of market penetration of connected and automated vehicles within a long planning horizon. In addition, Dr. Bhat is the Director of the recently funded Data-Supported Transportation Operations and Planning (D-STOP) Center (http://www.dstop.org/) that focuses on harnessing wireless technology for transportation planning and operations. Many of the D-STOP Center projects focus on research issues at the interface of advanced vehicle-to-infrastructure/vehicle-to-vehicle communications and connected, semi-autonomous, and autonomous vehicle systems. The current project, if funded, will have the benefit of leveraging the resources of the D-STOP Center while also providing matching funds for the D-STOP Center. In particular, Dr. Bhat will bring the knowledge gained from D-STOP projects, as well as the knowledge of the entire D-STOP research team (including faculty from the Wireless Networking and Communications Group of the Electrical and Computer Engineering Department), to help with important technology-related technical issues relevant to this project. As importantly, Dr. Bhat has undertaken a wide array of research and consulting projects involving the development of decision support systems for transportation planning projects. His combination of technical skills and experience in packaging information to support decision-making will be valuable to this project.

Dr. Bhat has been invited by state DOTs and MPOs around the country to provide workshops/primers on data analysis in the context of transportation issues. He is one of the two authors of the guide on discrete choice models (http://www.caee.utexas.edu/prof/bhat/COURSES/LM_Draft_060131Final-060630.pdf) prepared for the US Department of Transportation. This guide remains one of the most authoritative documents in model specification, estimation, and calibration. He has contributed to statistical estimation methods and tools for heterogeneous dependent variable modeling.

Dr. Bhat has received several recent honors and awards in recognition of his many contributions to safety modeling and travel behavior analysis, including the 2013 Humboldt Research Award from the Alexander von Humboldt Foundation, Germany, the 2013 Transportation Research Board (TRB) Pyke Johnson Award for the best paper (with a doctoral student and two colleagues) in the area of planning and environment, the 2009 S.S. Steinberg Award from the American Road & Transportation Builders Association (ARTBA), the 2008 Wilbur S. Smith Distinguished Transportation Educator Award from the Institute of Transportation Engineers (ITE), the 2007 TRB Pyke Johnson Award for the best paper (with doctoral students) in the area of planning and environment, the prestigious 2005 James Laurie Prize and the 2004 Walter L. Huber Award from the American Society of Civil Engineers (ASCE), the 2001 TxDOT Outstanding Research Innovation Honor, and the 2001 Fluor Centennial Teaching Fellowship in Engineering.

2. Research Staff Experience

Dr. Robert W. Heath Jr., P.E.
Phone: 512-686-8225, Email: rheath@utexas.edu

Dr. Robert Heath is the Cullen Trust Endowed Professor (#6) in the Department of Electrical and Computer Engineering at The University of Texas at Austin, and is the Director of the Wireless Networking and Communications Group, a center within UT Austin with 20 faculty members, 120 graduate students, and $5M of research expenditures each year. He is also President and CEO of MIMO Wireless Inc. and Chief Innovation Officer at Kuma Signals LLC.

Dr. Heath brings deep expertise in wireless communications to the project. Specifically related to the project, he is at the forefront of research on millimeter wave communication. He is a co-author of the first comprehensive book on millimeter wave (Millimeter Wave Wireless Communications published by Pearson in 2014), is leading several projects related to millimeter wave cellular communication, and has published key papers on systems analysis and beamforming algorithms for millimeter wave communication. He has also worked on many problems at the interface between communications and data mining, devising efficient algorithms for adapting the wireless communication link to achieve the highest performance in mobile propagation channels. The current project, if funded, will leverage the skills and expertise of the Wireless Networking and Communications Group, which is playing a major role in the D-STOP center on projects related to the use of radar for collision avoidance and enabling high data rates to fast vehicles. The project will also have visibility with the industrial affiliates of the WNCG including Crown Castle, CommScope, Qualcomm, Huawei, Cisco, National Instruments, and the Department of Defense.

Dr. Heath has been substantially involved with the IEEE (Institute for Electrical and Electronics Engineers) Vehicular Technology Society, including being an editor for their main journal, the IEEE Transactions on Vehicular Technology, and organizing and serving as technical co-chair for their main conference the IEEE Vehicular Technology Conference. He has many publications in both venues on topics related to the use of multiple antennas in wireless communication to achieve high capacity and better reliability.

Dr. Heath has high visibility in the wireless communications field. In 2014 he was named a highly cited researcher (only seven total in the Cockrell School of Engineering at UT Austin). He has guest edited for several important special issues including the IEEE Journal on Selected Areas in Communications special issue on limited feedback communication, and the IEEE Journal on Selected Topics in Signal Processing, and is on the steering committee for the top journal in wireless communications the IEEE Transactions on Wireless Communications. He has co-organized and had leadership roles at the key conferences in his field including the 2007 Fall Vehicular Technology Conference, the 2008 Communication Theory Workshop, the 2009 IEEE Signal Processing for Wireless Communications Workshop, the 2009 IEEE CAMSAP Conference, the 2010 IEEE International Symposium on Information Theory, the 2011 and 2013 Asilomar Conference on Signals, Systems, and Computers, the 2013 IEEE GlobalSIP conference (which he founded), and the 2014 IEEE GLOBECOM conference. Besides more than 400 conference and journal papers, he has 48 issued US patents for his work.

Dr. Heath has received several honors and awards in recognition of his contributions to signal processing and wireless communications including co-authoring papers that received best paper awards at conferences: IEEE Vehicular Technology Conference 2006 Spring, Wireless Personal Multimedia Communications Conference 2006, IEEE Global Communications Conference 2006, IEEE Vehicular Technology Conference 2007 Spring, and IEEE Radio and Wireless Symposium 2009, and a Grand Prize in the 2008 WinTech WinCool Demo Contest. He has also co-authored several journal papers that received awards including the 2010 and 2013 EURASIP Journal on Wireless Communications and Networking best paper awards, the 2012 Signal Processing Magazine best paper award, a 2013 Signal Processing Society best paper award, the 2014 EURASIP Journal on Advances in Signal Processing best paper award, and the 2014 Journal of Communications and Networks best paper award. He is a Fellow of the IEEE.

Dr. Joydeep Ghosh
Phone: 512-471-8980, Email: jghosh@utexas.edu

Dr. Joydeep Ghosh is the Schlumberger Centennial Chair in Electrical Engineering in the Department of Electrical and Computer Engineering at The University of Texas at Austin. He joined the UT-Austin faculty in 1988 after being educated at, (B. Tech '83) and The University of Southern California (Ph.D'88). He is the founder-director of IDEAL (Intelligent Data Exploration and Analysis Lab) (http://www.ideal.ece.utexas.edu/) and a Fellow of the IEEE. His research interests lie primarily in data mining and web mining, predictive modeling / predictive analytics, machine learning approaches such as adaptive multi- learner systems, and their applications to a wide variety of complex engineering and AI problems.

Dr. Ghosh brings deep expertise in machine learning and big data analytics, and their applications in solving complex enginering problems. He has published more than 350 refereed papers and 50 book chapters, and co-edited over 20 books on these topics. His research has been supported by the NSF, Yahoo!, Google, ONR, ARO, AFOSR, Intel, IBM, and several others. He has successfully completed several large projects that involve data driven decision making and predictive analytics, including control of a network of dams in Central Texas, internet scale personalization for Yahoo frontpage (then the most visited portal on the planet), and data-driven multi-vehicle detection, tracking and coordination system for the US Army.

Dr. Ghosh has received 16 Best Paper Awards over the years, including the 2005 Best Research Paper Award across UT and the 1992 Darlington Award given by the IEEE Circuits and Systems Society for the overall Best Paper in the areas of CAS/CAD. Dr. Ghosh has been a plenary/keynote speaker on several occasions such as ICDM'13, ICML'12 and KDIR'10 and has widely lectured on intelligent analysis of large-scale data. He served as the Conference Co-Chair or Program Co-Chair for several top data mining oriented conferences, including SDM'13, SDM'12, KDD 2011, CIDM'07, ICPR'08 (Pattern Recognition Track) and SDM'06. He was the Conf. Co-Chair for Artificial Neural Networks in Engineering (ANNIE) for 7 years, and the founding chair of the Data Mining Tech. Committee of the IEEE Computational Intelligence Society. He has also co-organized workshops on high dimensional clustering, Web Analytics, Web Mining and Parallel/ Distributed Knowledge Discovery, in the recent past.

Dr. Ghosh has served as a co-founder, consultant or advisor to successful startups (Stadia Marketing, Neonyoyo and Knowledge Discovery One) and as a consultant to large corporations such as IBM, Motorola and Vinson & Elkins. Dr. Ghosh teaches graduate courses on data mining and web analytics. He was voted as "Best Professor" in the Software Engineering Executive Education Program at UT.

Post Doc Researchers
Two post-doctoral researchers will assist the three faculty members listed above, and serve as the day-to-day managers of the efforts to develop conceptual and functional frameworks to combine communications and radar, design the route configurations for the tests with the three vehicles, and analyze data for the purpose of fine-tuning all algorithms and methods developed in the conceptual stage.

Visiting Professor
Dr. Nuria González is an expert in signal processing architectures for radio front-ends. She is working on many research problems related to exploiting sparsity in data which has applications to reducing complexity in both communication and radar algorithms. Her expertise in signal processing for communications and radar will be helpful in the tasks related to the design of joint waveforms for communications and radar at millimeter wave frequencies.

Graduate Research Assistants, at the MS or PhD level, will be selected on the basis of their particular skill set in areas pertinent to the study. The pertinent backgrounds include but not limited to engineering, computer science, analytical analysis, wireless communication, and other key components of the project.

3. Staffing Plan

Team Members: 15-1	Budget
Dr. Chandra Bhat will serve as Research Supervisor on this project. He will ensure all deadlines are met and will also provide quality assurance and control on all aspects of the project. His knowledge of vehicle dynamics, driver behavior, and bicyclist/pedestrian behavior will be critical in the development and customization of communication and radar-aided systems for transportation safety and reliability enhancement.	$17,187
Dr. Robert Heath will serve as a Co-PI on this project. He will lead efforts related to millimeter wave communication and radar, but will be heavily involved with all tasks including the testbeds.	$15,620
Dr. Joydeep Ghosh will serve as a Co-PI on this project, and will lead efforts related to applying machine learning and statistical models for sensor fusion, predictive analytics/forecasting and decision making.	$18,198
The two Post Doc Researchers will serve as the day-to-day managers of all research efforts.	$100,008
Visiting Professor, Dr. Nuria Gonzalez, will help in the tasks related to the design of joint waveforms for communications and radar at millimeter wave frequencies.	$30,000

Graduate students (MS and PhD level) will be selected on the basis of their particular skill sets in areas pertinent to this study. The pertinent backgrounds include but not limited to engineering, computer science, analytical analysis, wireless communication, and other key components of the project.	$193,200
Clerical Assistance: Administrative staff at UT Austin will work directly on this project to assist with project management, coordinating research meetings, coordinating monthly progress reports, organizing outreach events, and assisting with all technical documents and deliverables.	$20,379
Total	**$394,592**

4. Past Performance

The investigators have been involved with several TxDOT and other projects related to the subject area of the current project. The most relevant of these for the current project are listed below.

<u>Dr. Chandra Bhat: Selected Research Reports</u>

Deng, J., K. Lorenzini, E. Kraus, R. Paleti, M. Castro, and C.R. Bhat, "Business Process and Logical Model to Support a Tour-Based Travel Demand," Report 0-6759-1, prepared for the Texas Department of Transportation, August 2013.

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Bhat, C.R., J. Guo, S. Srinivasan, and A. Sivakumar, "Guidebook on Activity-Based Travel Demand Modeling for Planners," Product 0-4080-P3, prepared for the Texas Department of Transportation, October 2003.

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Sen, S. and C.R. Bhat, "The Impact of Demographics, Built Environment Attributes, Vehicle Characteristics, and Gasoline Prices on Household Vehicle Holdings and Use", Technical Report SWUTC/06/167550-1, prepared for the Southwest Region University Transportation Center of the U.S. Department of Transportation, September 2006.

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Bhat, C.R. and S. Nerella, "Develop GIS-Integrated Traffic Models for MOBILE6-Based Air Quality Conformity and TCM Analysis: A Summary," Project Summary Report 0-4377-S, prepared for the Texas Department of Transportation, October 2003.

Bhat, C.R. and S. Nerella, "User's Guide to GIS-based Applications for Traffic Inputs to MOBILE6 Emissions Factor Model," Report 0-4377-4, prepared for the Texas Department of Transportation, August 2003.

Dr. Chandra Bhat: Selected Research Projects

Tier 1 University Transportation Center, Research and Innovative Technology Administration (RITA), U.S. DOT, "Data-Supported Transportation Operations and Planning (D-STOP)," 9/30/13-9/30/17.

Federal Highway Administration, Exploratory Advanced Research Program, "Foundational Knowledge to Support a Long Distance Passenger Travel Demand Modeling Framework," 7/20/11-10/20/14.

Texas Department of Transportation, Project 0-6759, "Developing a Business Process and Logical Data Model to Support a Tour-based Travel Demand Model Design," 9/1/12-8/31/13.

Southern California Association of Governments (SCAG), "Household Evolution Model Development for SCAG Activity Based Model," collaborative project with Kostas Goulias (University of California, Santa Barbara) and Ram Pendyala (Arizona State University), 11/17/11-6/30/13.

Texas Department of Transportation, Project 0-6691, "Managing the TDM Process: Developing MPO Institutional Capacity," 9/1/11-2/28/13.

Southern California Association of Governments (SCAG), "SCAG Activity-Based Travel Demand Model Development: Development of SimAGENT," collaborative project with Kostas Goulias (University of California, Santa Barbara) and Ram Pendyala (Arizona State University), 4/01/09-12/31/12.

North Central Texas Council of Governments (NCTCOG), "Advanced Travel Demand Modeling: Choice Model Estimation Training," 1/19/11-9/30/12.

Transit Cooperative Research Program (TCRP), Project H-37A, "Characteristics of Premium Transit Services that Affect Choice of Mode," 5/28/10-5/31/12.

Strategic Highway Research Program 2 (SHRP2), Project C-10(A), "Partnership to Develop an Integrated, Advanced Travel Demand Model and Fine-Grained, Time-Sensitive Network," collaborative project with Stephen Lawe, AECOM, Mark Bradley, John Bowman, S. Travis Waller, Ram Pendyala, and Mohammad Hadi, 8/13/09-2/28/12.

Texas Department of Transportation, Project 0-6632, "Positive Feedback: An Examination of Current Approaches in Iterative Travel Demand Model Implementation," 9/1/10-8/31/11.

Texas Department of Transportation, Project 5-5178-03, "Measuring Access to Transit Service in Rural Transit Systems," 6/11/09-12/31/10.

Ohio Department of Transportation, "Sensitivity of Four-Step Versus Activity Based Models to Transportation System Changes," collaborative project with John Bowman (Bowman Research & Consulting, Mark Bradley (Bradley Consulting), David Schmitt (AECOM Consult, Inc.), and Ram Pendyala (Arizona State University), 9/1/08-11/30/10.

North Central Texas Council of Governments (NCTCOG), "Discrete Choice Modeling: Training and Technology Transfer," 10/1/09-9/30/10.

Texas Department of Transportation, Project 0-6544, "Appraisal of Available Analytic Tools to Assess Environmental Justice Impacts of Toll Road Projects," 9/1/09-8/31/10.

Texas Department of Transportation, Project 0-6210, "Adding Tour-Based Modeling to TxDOT's Travel Modeling Framework," 9/1/08-8/31/09.

Southwest Region University Transportation Center of the U.S. Department of Transportation, Project 169200, "A Comprehensive Analysis of Impact of Travel Time Reliability on Congestion Management Strategies," 9/1/08-8/31/09.

North Central Texas Council of Governments (NCTCOG), "CEMDAP – Testing and Enhancement," 1/1/08-12/31/08.

Texas Department of Transportation, Project 5-5178-01, "Measuring Access to Transit Service," 9/29/06-8/31/08.

Southwest Region University Transportation Center of the U.S. Department of Transportation, Project 167260, "Impacts of Demographic Shifts in Metropolitan Areas on the Transportation Network," 9/1/06-8/31/07.

Texas Department of Transportation, Project 0-4080, "Second Generation Activity-Based Travel Modeling System for Metropolitan Areas in Texas Accommodating Demographic, Land Use, and Traffic Microsimulation Components" (continuation), 9/1/04-8/31/05 and 9/1/05-8/31/06.

National Center for Environmental Research of the U.S. Environmental Protection Agency, "Integrating Land Use, Transportation and Air Quality Modeling," 9/16/04-9/15/08.

Texas Department of Transportation, Project 0-5178, "Measuring Access to Public Transportation Services," funded by TxDOT, 9/1/04-8/31/06

Southwest Region University Transportation Center of the U.S. Department of Transportation, Project 167240, "Time-of-Day Modeling of Person Trips Using Revealed Preference and Stated Preference Surveys," 9/1/03-8/31/05.

Texas Department of Transportation, Project 0-4080, "Second Generation Activity-Based Travel Modeling System for Metropolitan Areas in Texas Accommodating Demographic, Land Use, and Traffic Microsimulation Components," 9/1/03-8/31/04.

Southwest Region University Transportation Center of the U.S. Department of Transportation, Project 167550, "On Examining Household Vehicle Holdings and Usage Decisions," 9/1/04-8/31/06.

Texas Department of Transportation, Project 0-5176, "Conversion of Volunteer-Collected GPS Diary Data to Travel Time Performance Measures," 9/1/04-12/31/05.

Texas Department of Transportation, Project 0-4080, "Activity-Based Travel Demand Modeling for Metropolitan Areas in Texas," 9/1/00-8/31/03.

Texas Department of Transportation, Project 0-4377, "Develop GIS-Integrated Traffic Models for MOBILE6-Based Air Quality Conformity and TCM Analysis," 9/1/01-8/31/03.

Southwest Region University Transportation Center of the U.S. Department of Transportation, Project 167220, "A Methodology to Analyze the Effectiveness of Roadway Pricing Control Strategies Using Travel Survey Data," 9/1/00-8/31/02.

Southwest Region University Transportation Center of the U.S. Department of Transportation, Project 167800, "A Joint Model System of Mode Choice, Destination Choice, and Departure Time Choice," 9/1/99-8/31/01.

Texas Department of Transportation, Project 0-1838, "Transportation Control Measure Effectiveness in Ozone Nonattainment Areas," 9/1/98-8/31/01.

Dr. Robert Heath: Selected Publications

Bai, T. and R. W. Heath, Jr., "Coverage and Rate Analysis for Millimeter Wave Cellular Networks," to appear in the IEEE Trans. on Wireless, March 2014. Available at ArXiv.

Bai, T., A. Alkhateeb, and R. W. Heath, Jr., "Coverage and Capacity of Millimeter Wave Cellular Networks," to appear in IEEE Communications Magazine, February 2014.

Alkhateeb, A., O. El Ayach, G. Leus and R. W. Heath, Jr., "Channel Estimation and Hybrid Precoding for Millimeter Wave Cellular Systems," to appear in the IEEE Journal on Sel. Topics in Sig. Proc., special issue on Massive MIMO Communication, September 2013.
El Ayach, O., S. Abu-Surra, S. Rajagopal, Z. Pi, and R. W. Heath, Jr., "Spatially Sparse Precoding in Millimeter Wave MIMO Systems," IEEE Trans. on Wireless, vol. 13, no. 3, pp. 1499-1513, March 2014.

Valliappan, N., A. Lozano, and R. W. Heath, Jr., "Antenna Subset Modulation for Secure Millimeter-Wave Wireless Communication," IEEE Trans. on Communications, vol. 61, no. 8, pp. 3231-3245, Aug. 2013.

Daniels, R., J. N. Murdock, T. Rappapport, and R. W. Heath, Jr., "State-of-the-Art in 60 GHz," IEEE Microwave Magazine, vol. 11, no. 7, pp. 44-50, Dec. 2010.

Park, C.H., R. W. Heath, Jr., and T. Rappapport, "Frequency-Domain Channel Estimation and Equalization for Continuous-Phase Modulations with Superimposed Pilot Sequences," IEEE Trans. on Veh. Tech., vol. 58, no. 9, Nov. 2009.

Daniels, R. and R. W. Heath, Jr., "60 GHz Wireless Communications: Emerging Requirements and Design Recommendations," IEEE Vehicular Technology Magazine, vol. 2, no. 3, pp. 41-50, Sept. 2007.

Dohler, M., R. W. Heath, Jr., A. Lozano, C. Papadias, R. A. Valenzuela, "Is the PHY Layer Dead?," IEEE Communications Magazine, vol. 49, no. 4, pp. 159-165, April 2011.

Cui, S., R. W. Heath, Jr., and G. Leus, "Signal Processing for Networking and Communications [In the Spotlight]," IEEE Signal Processing Magazine, vol. 28, no.5, pp. 151-152, September 2011.

Boccardi, F., R. W. Heath, Jr., A. Lozano, T. L. Marzetta, and P. Popovski "Five disruptive technology directions for 5G," IEEE Communications Magazine, vol. 52, no. 2, pp. 74-80, Feb. 2014.

McKay, M. R., I. B. Collings, A. Forenza, R. W. Heath, Jr., "Multiplexing / Beamforming Switching for Coded-MIMO in Spatially-Correlated Rayleigh Channels," IEEE Trans. on Veh. Tech., vol. 56, no. 5, part 1, pp. 2555-2567, Sept. 2007.

Bhagavatula, R., C. Oestges, and R. W. Heath, Jr., "A New Double Directional Channel Model Including Antenna Patterns, Array Orientation and Depolarization," IEEE Trans. on Veh. Tech., vol. 59, no. 5, pp. 2219-2231, June 2010.

Bhagavatula, R., R. W. Heath, Jr., and K. Linehan, "Performance Evaluation of MIMO Base Station Antenna Designs," Antenna Systems & Technology, vol. 11, no. 6, pp. 14-17, Nov. / Dec. 2008.

Bhagavatula, R., R. W. Heath, Jr., A. Forenza, and S. Vishwanath, "Sizing up MIMO Arrays," IEEE Vehicular Technology Magazine, vol. 3, no. 4, pp. 31-38, Dec. 2008.

Daniels, R. and R. W. Heath, Jr., "Link Adaptation with Position/Motion Information in Vehicle-to-Vehicle Networks," IEEE Trans. on Wireless, vol. 11, no. 2, pp. 505-509, February 2012.

Daniels, R., C. Caramanis, and R. W. Heath, Jr., "Adaptation in Convolutionally-Coded MIMO-OFDM Wireless Systems through Supervised Learning and SNR Ordering," IEEE Trans. on Veh. Tech., vol. 59, no. 1, 2010, pp. 114-126.

Love, D. J. and R. W. Heath, Jr., "Limited Feedback Diversity Techniques for Correlated Channels," IEEE Trans. on Veh. Tech., vol. 55, no. 2, pp. 718-722, March 2006.

Huang, K., J. G. Andrews, and R. W. Heath, Jr., "Performance of Orthogonal Beamforming for SDMA with Limited Feedback," IEEE Trans. on Veh. Tech., vol. 58, no. 1, pp. 152-164, Jan. 2009.

Peters, S. W. and R. W. Heath, Jr., "Cooperative Algorithms for MIMO Interference Channels", IEEE Trans. on Veh. Tech., vol. 60, no. 1, pp. 206-218, Jan. 2011.

El Ayach, O., S. W. Peters, and R. W. Heath, Jr., "Feasibility of Interference Alignment of Measured MIMO-OFDM Channels", IEEE Trans. on Veh. Tech.. vol. 59. No. 9. pp. 4309-4321, Nov. 2010.

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Truong, K. T., and R. W. Heath, Jr., "Joint Transmit Precoding for the Relay Interference Broadcast Channel," IEEE Trans. on Veh. Tech., vol. 62, no. 3, pp. 1201-1215, March 2013.

Lo, C., S. Vishwanath and R. W. Heath, Jr., "An Energy-Based Comparison of Long-Hop and Short-Hop Routing in MIMO Networks," IEEE Trans. on Veh. Tech., vol. 59, no. 1, pp. 394-405, January 2010.

Lo, C., S. Vishwanath, and R. W. Heath, Jr., "The Impact of Channel Feedback on Opportunistic Relay Selection for Hybrid-ARQ in Wireless Networks," IEEE Trans. on Veh. Tech., vol. 58, no. 3, pp. 1255-1268, March 2009.

Lo, C., R. W. Heath, Jr., and S. Vishwanath, "Relay Subset Selection in Wireless Networks Using Partial Decode-and-Forward Transmission," IEEE Trans. on Veh. Tech., vol. 58, no. 2, pp. 692-704, Feb. 2009.

Peters, S. W. and R. W. Heath, Jr., "The Future of WiMAX: Multihop Relaying with IEEE 802.16j," IEEE Communications Magazine, vol. 47, no. 1, pp. 104-111, Jan. 2009.

<u>Dr. Robert Heath: Selected Research Projects</u>

Tier 1 University Transportation Center, Research and Innovative Technology Administration (RITA), U.S. DOT, "Data-Supported Transportation Operations and Planning (D-STOP)," 9/30/13-9/30/17.

CIF: Small: Interference Modeling and Management for Heterogenous Networks, National Science Foundation, 9/1/12-8/31/15

Fundamental Limits, Self-organization and Context-Awareness for Integrated Cellular and D2D Architectures, 9/13 to 8/16.

CIF: Small: Realizing Millimeter Wave Communication Systems, National Science Foundation. 9/13 to 8/16.

mmWave Ad Hoc Networks, Army Research Labs, 9/14 to 8/17

Perceptual Video Quality Aware Wireless Networks, Intel and Cisco,
9/1/10-8/31/2013.

Measurements of MIMO Performance Under Army Operational Conditions, Batelle,
10/1/09 – 9/30/10

Distributed and Structured Interference Alignment for Mobile Ad Hoc Networks, Office of Naval Research, 1/1/10-8/31/12

High Throughput via Cross-Layer Interference Alignment for Mobile Ad Hoc Networks, Army Research Labs, 9/1/10-8/31/2013

Interference Alignment Measurement Study, DARPA, 3/5/09-7/09/10

Research on Massively Broadband Millimeter Wave Integrated Circuits and Wireless Sensors at The University of Texas at Austin, Army Research Labs, 9/1/08-8/31/10

Coordinated Wireless Networks for the Broadcast and Multicast Channels, Samsung, 1/1/008-1/15/09

Signal Processing for Special Manifolds with Applications to Wireless Communication
National Science Foundation, 8/28/08-8/31/11

Dr. Joydeep Ghosh: Selected Research Reports

Park, Y. and J. Ghosh, "CUDIA: Probabilistic Cross-level Imputation using Individual Auxiliary Information", *ACM Transactions on Intelligent Systems and Technology*, spl. Issue on Health Informatics, 4(3), 2013, pp. 66:1 – 66:24.

Park, Y. and J. Ghosh, "Ensemble of α-Trees for Imbalanced Classification Problems", in *IEEE Trans. Knowledge and Data Engineering*, 26(1), Jan 2014, pp. 131-143.

Acharya, A., E.R. Hruschka and J. Ghosh, "An Optimization Framework for Semi-Supervised and Transfer Learning using Multiple Classifiers and Clusterers", *ACM Transactions on Knowledge Discovery from Data, 2014*

Ghosh, J. and A. Acharya, "Cluster Ensembles", *WIREs Data Mining and Knowledge Discovery* 1 (4), July/Aug 2011, pp. 305-315.

Jun, G. and J. Ghosh, "Spatially Adaptive Semi-Supervised Learning with Gaussian Processes for Hyperspectral Data Analysis", *Statistical Analysis and Data Mining*, Wiley, 4(4), Aug 2011, pp. 358-371.

Jun, G. and J. Ghosh, "Semi-supervised Learning of Hyperspectral Data with Unknown Land Cover Classes", *Proc. IEEE Transactions on Geoscience and Remote Sensing (TGRS),* 51(1), Jan 2013, pp. 273-282.

Mittal, A., G S. Muralidhar, J Ghosh and Alan C. Bovik "Blind Image Quality Assessment Without Human Training Using Latent Quality Factors", *IEEE Signal Processing Letters*, 19(2), Feb 2012, pp. 75-78.

Deodhar, M. and J. Ghosh, "SCOAL: A Framework for Simultaneous Co-Clustering and Learning from Complex Data", in *ACM Transactions on Knowledge Discovery from Data*. 4(3), Oct 2010, pp. 11:1-11:31

Liu, A., G. Jun and J. Ghosh, "A Self-Training Approach to Cost Sensitive Uncertainty Sampling", in *Machine Learning Journa*l, Volume 76, Numbers 2-3 / September, 2009 , pp. 257-270.

Banerjee, A., S. Merugu, I. Dhillon and J. Ghosh, "Clustering with Bregman Divergences", *Jl. of Machine Learning Research (JMLR),* 6(Oct):1705--1749, 2005.

Banerjee, A., and J. Ghosh, "Scalable Clustering Algorithms with Balancing Constraints", in *Data Mining and Knowledge Discovery*, 13 (3), Nov 2006, pp. 365-395.

Banerjee, A., S. Merugu, I. Dhillon and J. Ghosh, "Clustering with Bregman Divergences", *Jl. of Machine Learning Research (JMLR),* 6(Oct):1705--1749, 2005.

Banerjee, A., and J. Ghosh, "Scalable Clustering Algorithms with Balancing Constraints", in *Data Mining and Knowledge Discovery*, 13 (3), Nov 2006, pp. 365-395.

Tumer, K. and J. Ghosh, "Bayes Error Rate Estimation using Classifier Ensembles", *International Journal of Smart Engineering System Design*, Volume 5, Number 2, April-June 2003, pp. 95-109.

Tumer, K. and J. Ghosh, "Robust combining of disparate classifiers through order statistics", in *Pattern Analysis and Applications*, spl. Issue on Fusion of Multiple Classifiers, Vol. 5, No. 2, 2002, pp. 189-200.

Dr. Joydeep Ghosh: Selected Research Projects

PI, "III: Small: Core: Monotonic Retargeting: A Scalable Learning Framework for Determining Order", NSF, 09/01/14 - 08/31/17

Co-PI: "RI: Small: Intelligent Autonomous Video Quality Agents" (with A. Bovik, PI), NSF, 9/11-8/14.

PI, "Best Next Product", USAA, 12/12-1/14

PI, "SK Telecom Data Mining and Data Analysis", SK Telecom, 09/01/12 – 07/31/13

PI, "III: Small: Simultaneous Decomposition and Predictive Modeling on Large Multi-Modal Data", NSF, 09/01/10 - 08/31/13

PI: "Inter-Agency “Co-opetition” via Hidden Web Databases", NHARP, 07/10 – 08/12. With G. Das and B. Gao

PI, "Advanced learning and integrative knowledge transfer approaches to remote sensing and forecast modeling for understanding land use change", NSF, 09/01/07 - 08/31/10.

5. Research Facilities

The University of Texas at Austin

The University of Texas at Austin (UT-Austin) is the largest university in Texas and has a worldwide reputation as a leader in engineering education and research. The Department of Civil, Architectural, and Environmental Engineering (CAEE) within the Cockrell School of Engineering has consistently been ranked among the top programs offering research and engineering education in the country. Various experimental computer systems with advanced architecture are available on campus. UT-Austin also has one of the largest library holdings among academic institutions in the world. The McKinney Engineering Library provides access to all major technical and professional journals for the engineering disciplines. The library system also provides access to major on-line bibliographic, publication, and research and retrieval database services.

Center for Transportation Research

The Center for Transportation Research (CTR) is a multi-disciplinary transportation research and educational organization established within the Bureau of Engineering Research of the Cockrell School of Engineering at UT-Austin. CTR's annual research budget exceeds $13 million, making it the second largest university-based center in the U.S. CTR programs are conducted by full-time faculty members and graduate students supported by a professional research staff and a small administrative staff. CTR maintains a transportation library with over 17,000 titles of transportation related materials. The library contains copies of reports generated by TxDOT's research program as well as state, federal, national, and international materials. The CTR library maintains a web catalog at http://library.ctr.utexas.edu. The library has two full-time staff members and two part-time graduate assistants who are available to provide reference services for all of their patrons.

The facilities at CTR and UT-Austin will be utilized. These include computer hardware and software, graphics facilities, laboratories and testing sites, and the various offices and conference rooms normally used for work and meetings.

Wireless Networking and Communications Group

The Wireless Networking and Communications Group (WNCG) is an interdisciplinary center for research and education at The University of Texas at Austin with an emphasis on industrial relevance. Founded in 2002, the group includes twenty faculty from the Departments of Electrical and Computer Engineering, Aerospace Engineering, Mathematics, and Computer Sciences. WNCG currently has over 130 graduate and undergraduate students as well as an ever-changing number of research scientists, postdoctoral fellows and industry visitors.

WNCG has an exceptional track record of fostering collaborations with industry leaders through the Industrial Affiliates Program. Current Industrial Affiliates include National Instruments, Samsung, AT&T, Dell, Cisco, DOCOMO, CommScope, Qualcomm, Yokogawa, Crown Castle, Huawei and the United States Department of Defense.

The WNCG houses the MIMO Wireless Lab, which is run by Dr. Heath. It features a suite of Agilent test equipment including a vector signal analyzer, spectrum analyzer, signal generator, digital oscilloscope, and digital multimeter, and an interference alignment testbed based on the USRP N210 software defined radio platform (see e.g. http://www.profheath.org/research/interference-alignment/mimo-ofdm-interference-alignment-testbed/). The testbed implements 6x6 spatial multiplexing MIMO-OFDM transmission as well as over-the-air interference alignment with three 2x2 user pairs. The equipment is used for two different prototyping efforts. In one effort, the entire physical layer is implemented in a combination of mathscript and LabVIEW on a PC to allow for flexible reconfiguration. In another effort, the physical layer is implemented in a combination of C++ and Python and runs on an embedded target. The prototype, consequently, allows the study of different algorithms and exposes implementation constraints. Additional measurement and test capabilities include vflexible equipment from National Instruments including RF upconverters, downconverters, and high speed A/D and D/A hardware.

Machine Learning Facilities

The IDEAL lab (http://www.ideal.ece.utexas.edu/) directed by Prof. Ghosh at The University of Texas at Austin is a premier center of excellence in data mining and pattern recognition. It is located on the 3rd floor of the ACES building, with approximately 1500 sq.~ft of lab space, three separate offices for visiting faculty and post-docs, and state-of-the-art facilities such fiber as well as gigabit ethernet to every desk. Dedicated computing resources include rack mounted 32x4 core servers and 20+ workstations. IDEAL members have access to the supercomputing facilties of the Texas Advanced Computer Center (www.tacc.utexas.edu), including the ACES Visualization Lab for high-end data modeling and visualization, including a Hadoop/Spark cluster with 128 nodes, and over 100 TBytes of storage.

Data Mining Software: IDEAL has developed several software packages that are licensed under GPL and used by several researchers in the data mining community. Popular packages include GeneDiver for multiresolution analysis of microarray data, similarity based clustering and visualization modules, ensemble shells/wrappers, software for scalable clustering and co-clustering, Mutual Information based feature extractors, probabilistic principal surfaces, and several packages tailored for analysis of hyperspectral images. We also have expertise in and access to commercial/public domain statistical analysis and data mining software, including SAS Enterprise Miner and IBM intelligent Miner, (Revolution) R, Python, Matlab, SPSS and Hadoop.