CPS: Synergy: Collaborative Research: Enabling Smart Underground Mining with an Integrated Context-Aware Wireless Cyber-Physical Framework

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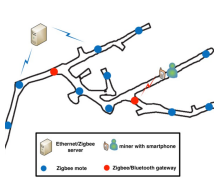
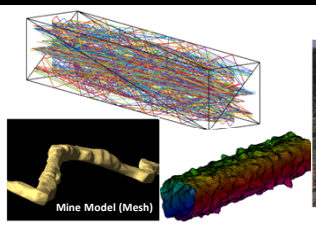
Mission: The aim of this project is to design, prototype, and test a novel wireless cyber-physical framework of low cost, energy-efficient, and reliable sensor nodes and commodity smartphones for monitoring, tracking, and communication, to improve miner safety in underground mines

Three cross-disciplinary thrusts:

- develop energy-efficient and error-tolerant **indoor (underground) localization** to locate individual miners and groups of miners
- enable co-existence of high quality **voice streams with environmental sensor data** streams in low-power wireless mesh networks
- **characterize wireless signal behavior** with EM modeling, based on real measurements, to guide placement of wireless nodes in tunnels

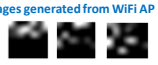




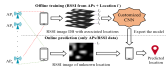
Robust and Energy-Efficient Indoor Localization

Deep Learning for Indoor Navigation and Localization

- Convolutional Neural Networks (CNNs) for fingerprinting-based indoor localization
  - images generated from WiFi AP data



- CNN trained with WiFi AP data across multiple indoor paths
- Deployed on smartphones; hierarchical decision trees for further accuracy
- Average localization error < 2 meters
- Ongoing: adapt to ultra wide band (UWB)

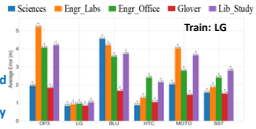


A. Mittal, S. Tiku, S. Pasricha, "***Adapting Convolutional Neural Networks for Indoor Localization with Smart Mobile Devices***," ACM Great Lakes Symp. on VLSI (GLSVLSI), May 2018. **(Best Paper Award)**

Enabling Portability in Indoor Navigation and Localization

- Indoor localization frameworks can be unreliable and unpredictable across mobile devices!
  - Wireless chipsets are very diverse
  - PortLoC framework for device heterogeneity-resilience
  - Uses Spearman's Correlation Coefficient (SCC), Zero Normalized Cross-Correlation (ZNCC)
  - Allows noisy and error-prone WiFi fingerprint readings to be correlated to data in fingerprint database
  - Significant improvement in accuracy across localization frameworks

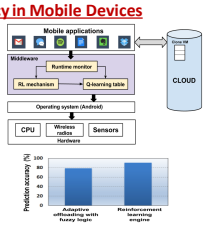
Smartphone	Chipset	Android
OnePlus 3 (OP3)	Snapdragon 820	8.0
LG V20 (LG)	Snapdragon 820	7.0
Moto Z2 Force (MOTO)	Snapdragon 835	8.0
Samsung S7 (S57)	Snapdragon 820	7.0
HTC U11 (HTC)	Snapdragon 635	8.0
BLU Vivo 8 (BLU)	MediaTech Helio P10	7.0



S. Tiku, S. Pasricha, "***PortLoc: A Portable Data-driven Indoor Localization Framework for Smartphones***", to appear, IEEE Design and Test, 2019.

Offloading for Energy-Efficiency in Mobile Devices

- Offloading from mobile devices to servers
  - Improves performance of localization apps
  - Saves energy and extend battery life
- Middleware framework for offloading
  - Reinforcement (Q) learning – reward based
- Factors considered at runtime
  - App- and user-specific data usage patterns
  - Network signal strength and availability
  - Wireless network consistency observations
  - Potential for energy or QoS benefits
- Cab achieve significant improvements
  - 30% battery life, 25% response time

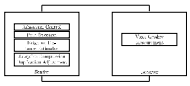


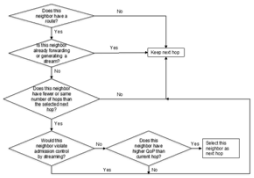
A. Khune, S. Pasricha, "**Mobile Network-Aware Middleware Framework for Energy Efficient Cloud Offloading of Smartphone Applications**", IEEE Consumer Electronics, Vol. 8, Iss. 1, Jan 2019.

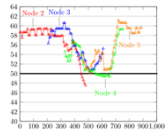
Voice/Data Streaming in Low Power Wireless Networks

Voice Convergecast in Mobile Low Power Wireless Networks

- Integrated routing and admission control
  - Maximize number of admitted streams
  - Key concept: quality of path (minimum number of contention domains affected on a path between a node and a sink)
  - Multi-layer approach
  - Deployed on Arduino Due and Xbee S1
  - 3 concurrent mobile streams can be supported
  - Ongoing: voice multicast



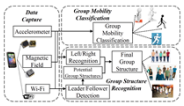


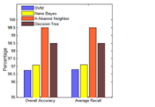


M. Adkins, Q. Han, S. Pasricha, "***Quality-aware Voice Convergecast in Mobile Low Power Wireless Networks***," IEEE International Conference on Mobile Computing, Applications and Services (MobiCASE), Hangzhou, China, June 14-15, 2019.

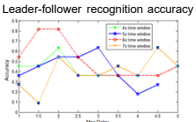
Recognition of Group Structure and Mobility Level using Mobile Devices

- Group characterization is important for public safety
  - Not use accurate locations
  - Use data from accelerometer, magnetic field, and Wi-Fi
  - Fine-grained mobility classification: stationary, strolling, walking, running
  - Structure recognition based on relative relations: leader-follower, left-right
  - Implemented/evaluated on Android phones
  - KNN outperforms SVM, NB, DT in mobility classification

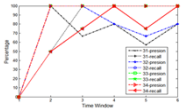




Leader-follower recognition accuracy



Left-right recognition accuracy

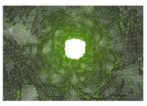


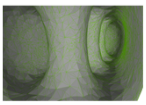
H. Du, Z. Yu, F. Yi, Z. Wang, Q. Han, B. Guo, "***Recognition of Group Mobility Level and Group Structure with Mobile Devices***," IEEE Tran. Mobile Computing (TMCI), Vol. 17, No. 4, April 2018.

EM Modeling/Characterization in Underground Mines

Modeling of EM Propagation in Underground Mines

- Data acquisition and surface reconstruction
  - Scan mine into point cloud data
  - Topologically correct surface reconstruction guarantees
  - Algorithm to convert from triangular mesh to quads



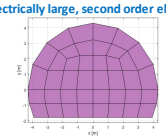


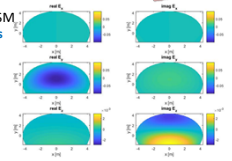
- Efficient approach to rendering real-world structures and objects for analysis by computational EM solvers
- Hybridization of several methods and solvers
  - Diakoptic/GSM domain decomposition
  - Subsystems solved using Finite Element Method (FEM), Method of Moments (MoM), Ray Tracing (RT) method, and Vector Parabolic Equation (VPE) method

GSM Analysis Using Piecewise Full-Wave Solutions

- Generalized scattering matrix (GSM) domain decomposition
  - Independent analysis of each subsystem with dedicated solvers
  - Solutions stitched together using diakoptics method with GSM

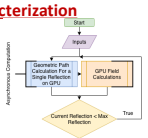
- 2D FEM Massif Tunnel modelling with GSM
  - Electrically large, second order elements

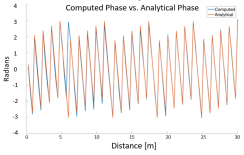


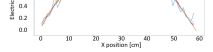


Ray Tracing for Wireless Signal Characterization

- Shooting bouncing ray (SBR) technique for wireless signal characterization
  - Problems computationally intractable with full-wave solvers, e.g., > 10,000 wavelengths, like mines
  - Leverages GPU acceleration (NVIDIA CUDA, OptiX)
  - Asynchronous computation
  - Coalesced memory access for efficient ray spawning







Societal Impact:

- The project will enable a broad range of sensing, tracking, and communication applications for extreme subterranean and noisy indoor environments
  - will benefit from the reduced cost, greater flexibility, and better energy-efficiency of our proposed wireless infrastructure
  - e.g. #1, search/rescue in buildings, tunnels, and subway systems
  - e.g. #2, safer cave exploration, underground archaeological digs
- Network users, designers, and practitioners will be able to exploit symbiotic relationship between wireless signal propagation and technology that relies on such signals
  - to achieve guarantees about performance, energy-use, and quality
- Individual components will also find broad applicability
  - e.g., wireless signal propagation modeling will help radio-wave propagation characterization in subway and railway tunnels/stations, and modern communication-based train control (CBTC) systems

Education and Outreach:

- New Vertically Integrated Project (ViP) and Capstone Project on 'Indoor Localization' created to engage sophomore, junior, and senior undergraduate students with graduate students
  - 17 undergraduates have worked on wardriving robot design, mobile app, voice streaming on LPWLAN, wireless signal characterization

- Multiple women students recruited and active on project
  - 2 undergrad and 2 graduate students
- Results from project have been integrated into existing undergrad and graduate courses

Broader Research Impact:

- The outcomes of the project will result in a CPS for tracking, monitoring, and communication in underground mines
  - normal conditions, and in emergency response and rescue operations
- Deployment and testing in real underground mines
  - will help validate the developed scientific principles in the real world
- The attainment of this outcome will *transform* the lives of hundreds of thousands of miners in the USA that work in high stress and hazardous underground mines
  - especially as the desire to reduce reliance on other countries for minerals has led to an upswing in mining activity in recent years
- Our three synergistic thrusts are foundational and can be applied to a broad range of applications
  - wherever emphasis is on creating smarter workplaces, sustainably operating in extreme environments, and improving human safety

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