Summary of the active wireless research award CNS:1642982

Research vision: The amount of mobile data traffic is exploding in the United States and across the world. Today, this mobile traffic is served almost exclusively by frequency bands below 6 GHz. To serve this traffic in the future, there is interest in using under-utilized spectrum, specifically at millimeter-wave (mmWave) frequencies in the 28-100 GHz range. Future systems operating in 28-100 GHz would have access to very large bandwidths in licensed or unlicensed bands. In the past, the challenging propagation conditions and radio frequency (RF) hardware constraints have made mmWave wireless access impractical. Recent advances in mmWave analog and digital processing have made cost-effective commercial mmWave systems a possibility. However, the propagation conditions and unique challenges on the network and physical layers imposed by the mmWave hardware solutions still remain. In addition to using non-traditional frequencies, 5G and beyond networks are expected to have increased density and mobility. The challenge with supporting simultaneously the high density and high mobility requirements of future wireless services is understanding how to architect the networks to allow adaptation, incorporate the channel and network condition information available, and control in real-time the networks at all layers. These networks must seamlessly enable handover, QoS support, network self organization, channel estimation, users' location tracking, etc.

Our active proposal CNS-1642982 "*EARS: Collaborative Research: Real-time Control of Dense, Mobile, Millimeter Wave Networks Using a Programmable Architecture*" explores the potential offered by mmWave bands as a solution to the increasing traffic demand (network density) and increasing mobility of wireless services. To enable a network-level adaptation, the proposed work uses the tools of software-defined network (SDN). An SDN architecture allows controllers to run applications, interface with database and cloud-based servers, and adapt the radios and lower-layers. The level of flexibility and adaptability required of mmWave make SDN a natural fit for mmWave networks.

Goals of the project: the goals of the project were: (1) To develop a software-defined networking (SDN) architecture for mmWave systems that enables network-wide adaptation and a high degree of programmability. Our approach provided significant advantages over standard cellular architectures that use conservative methods for resource allocation, resulting in higher efficiency in terms of resource utilization. Our methods and tools were designed to meet the challenging goals of 5G demand by adapting network behavior to local network conditions in real time to optimize spectral efficiency. (2) To design, implement, and validate the protocols and abstraction layers for ubiquitous high-performance mmWave networks that leverage flexible spectrum sharing as well as advanced adaptation and resource allocation techniques. (3) To design energy-efficient beam-alignment algorithms and control signaling techniques for mobile mmWave networks, with the goal of minimizing the communication overhead while maximizing the communication performance. (4) To design network-level medium-access control coordination protocols to support a large number of users with minimal control overhead, and to achieve diversity in fast-varying environments. (5) To design a cloud-based "multi-layer radio environment map" (ML-REM) database that can provide a rich set of real-time estimates and average statistics of environmental parameters for location-based real-time control of communication parameters. (6) To acquire mmWave propagation measurements in several locations and propagation models to serve as input conditions for the ML-REM database.

Activities and Accomplishments: as part of the project, we have carried out the following major activities and accomplishments. We investigated and published a novel design for low-overhead beam-alignment protocols that optimize the trade-off between the communication overhead incurred for beam-alignment and the communication performance in terms of delay, throughput, and power. We designed beam-alignment protocols robust to noise, fading, and beam imperfections, by using error correction codes and multi-armed bandits. We designed and published a framework to track time-varying mmWave channels based on Bayesian multi-armed bandits, which combines a synthesis of sparse Bayesian learning and Kalman filtering and smoothing.

To leverage learned location-specific and mobility and blockage dynamics, we designed and published a framework based on partially observable Markov decision processes, that allows to automatically optimize adaptive strategies for beam-alignment, data communication and handover in mobile mmWave networks. This framework can be interfaced with the ML-REM to define optimal adaptive control strategies for the specific propagation environment the user is operating within.

In our proposed ML-REM framework, channel measurements are collected in the ML-REM database, along with side information such as estimated users' positions (acquired, for instance, through GPS) and beam indices. The database is then queried to provide signal strength predictions over the beam space. We implemented signal processing techniques based on tensor completion to generate these predictions based on past measurements. These predictions are then used to narrow down the search space to a small number of beams most likely to succeed during the beam alignment procedure. We demonstrated numerically the ability to perform accurate and fast beam-alignment with small training overhead.

We conducted and published results from two mmWave measurement campaigns: one at the United States Naval Academy in Annapolis, Maryland and one in Boulder, Colorado. For the first campaign, we collected measurements at various locations around the campus to characterize propagation conditions in a suburban-type environment. The emphasis was characterizing path loss for large-scale propagation modeling and single-input multiple-output (SIMO) for multipath evaluation. Our second campaign characterized propagation through foliage in a coniferous forest. The emphasis was characterizing large-scale path loss in addition to scattering. Using our measurement data, we constructed site-specific models to explore tuning channel model parameters according to local geographic features in an environment. We compared our results to several traditional suburban and forest propagation models, demonstrating the superior performance of our site-specific approach. We are currently planning for a measurement campaign in the Purdue campus to further refine our modeling technique.

We are currently utilizing our measurement data in conjunction with several standard 5G channel models and our site-specific geometric feature approach to build the ML-REM. We are also testing our approach with the prediction and adaptation algorithms developed in the project.

Intellectual Merit: This work addresses the theoretical and experimental issues that are impeding the deployment of mmWave wireless broadband systems. It develops and analyzes adaptive techniques that increase network achievable rates. It focuses on the interplay between network-level optimization and physical layer communication, sounding, and control. The optimization framework is based on programmability, which is enabled by the SDN framework. The SDN interfaces with a cloud-based Multi-Layer Radio Environment Map (ML-REM) that builds upon the database-enabled side information techniques pioneered for the 3.5 GHz band. Over-the-air data obtained through propagation measurements are used to construct the ML-REM. The experimental results have been integrated into theoretical models for continuous improvement and testing.

Broader Impacts: The research addresses the global need for ubiquitous wireless broadband by enabling new frequencies to be used for transmission in low-cost networks. This would have technological and economic impact by allowing high throughput wireless broadband access to be deployed worldwide. The proposed work had educational impact through course development at Purdue, Texas A&M, and the US Naval Academy. The research is being integrated into an existing Vertically Integrated Projects (VIP) team at Purdue and a new VIP team at Texas A&M.

Supplemental experimental validation on the Powder testbed

Goals, Milestones, and Predicted outcomes: The goal of the proposed experimental plan is to: (1) Collect propagation measurements at mmWave frequencies; demonstrate the feasibility of our beamfinding and beamsteering algorithms *in situ*; (2) Demonstrate a proof-of-concept implementation of the radio environment map at sub-6GHz frequencies with massive MIMO. These activities will complement the existing project's research and development activities by expanding our current measurement data with a much richer set of data, at both mmWave and sub-6GHz frequencies. We predict that these activities will demonstrate the feasibility of a fully automated approach for learning site-specific features of the propagation environment, that could be useful to speed up beam steering algorithms, and will provide the research community with a proof-of-concept implementation of the ML-REM architecture proposed in our existing project. We plan to widely disseminate our Powder experimental results via publication of one or more journal articles.

More specifically, we propose to carry out two main research activities:

Mobile mmWave propagation measurements and beam-tracking To complement our measurement campaigns, we plan to perform additional measurements at 28GHz, using our own mmWave front end. Although Powder does not have mmWave capabilities, it has a unique "bring-your-own-device" architecture built into it. Specifically, it is designed to allow third-party equipment to be deployed in the overall network, and be integrated with the rest of the platform and its experimental workflow. This capability is ideal for our mmWave front end. Our 28 GHz up- and downconverters were designed to interface with a USRP software-defined radio and provide full-duplex operation on any given link. For both measurement campaigns, propagation data was collected using a USRP B210 and control PC running GNU Radio. Operating at full output power, we have achieved link distances of up to 1.0 km in a campus environment using horn antennas; we expect to achieve similar ranges in the Powder testbed.

For our proposed experiment, one endpoint of our link will be mounted on one of the eight rooftop nodes available in the Powder testbed. Each of these nodes has two N310 and two X310 USRPs connected via fiber backhaul to a computing cluster, which will be used to store propagation measurements. The other link endpoint will be mounted on the roof of a van, with a control PC and operator inside the van. Antennas at each endpoint will be mounted on a computer controlled dual axis (azimuth and elevation) positioner, allowing us to mechanically steer our antennas. This positioner is under development and expected to be ready for our Purdue measurement campaign.

Although mechanically steering beams is slow, it does provide us with opportunities for demonstrating the feasibility of our location-based beamfinding and beamsteering algorithms *in situ*. For evaluating beamfinding algorithms, the van will be parked at multiple stationary locations on the Utah campus. Additionally, we will collect propagation measurement data from Salt Lake City, adding to our measurement database and providing us with a unique opportunity to evaluate the broad applicability of our site-specific propagation models. In our measurement campaigns to date, we have used a manual approach to beam-alignment for both static and mobile measurements; the Purdue campaign should demonstrate the feasibility of electromechanically and automatically steering and maintaining our antenna alignment. The Powder testbed will demonstrate the feasibility of a fully automatic and programmable approach for collecting measurements in a cloud, learning the propagation map, and use this map to automatically steer and maintain alignment.

Massive MIMO and ML-REM proof-of-concept: Powder has purpose built infrastructure to enable a broad range of massive MIMO related research, including beamforming, scheduling, interference management, etc. Although our original proposal focuses on mmWave frequencies, it is of significant practical interest to determine whether a site-specific propagation model at lower frequencies, such as the one developed in our proposal for mmWave, can be used to perform channel predictions at lower frequencies. Despite the radically different propagation behaviors of sub-6GHz and mmWave frequencies, such as the richer scattering characteristic of the former relative to the latter, we contend that a ML-REM approach similar to the one proposed in our existing project would be extremely beneficial to speed up channel estimation and beamforming in massive MIMO settings. This approach would enable base stations with massive MIMO capabilities to collect propagation measurements, store them in a cloud-based database, learn site-specific propagation models, and use this information to make channel predictions. In turn, these predictions can be used to optimize massive MIMO channel estimation and beamforming algorithms. Ultimately, the Powder testbed will provide us with a unique opportunity to design a proof-of-concept implementation of the ML-REM database and highly adaptive programmable architecture proposed in our existing proposal.

Potential impact: The proposed experimental activities will have an impact on the design of practical beam-alignment, beam-tracking, channel estimation and beamforming algorithms that leverage location-specific propagation conditions at mmWave frequencies and at lower frequencies with massive MIMO capabilities. This could have an enormous impact on the industrialization and standardization of fast channel estimation algorithm for massive MIMO, that exploit location-specific propagation conditions learned in the ML-REM database. In addition, installing our system on a PAWR testbed will provide us with an opportunity to validate our theoretical work *in situ* and demonstrate that our research is pertinent to a complex real-world propagation environment.

Evaluation plan: In order to assess the success of the proposed experimental research activities, we plan to use the following metrics of success: (1) the beam-steering algorithms at mmWave will be evaluated by measuring the evolution of signal strength over time, which directly measures the prediction capabilities of our propagation maps, and the ability of our steering algorithm to maintain alignment between transmitter and receiver; (2) the ML-REM proof-of-concept will be evaluated by comparing the channel predictions provided by the propagation map, with actual massive MIMO channel measurements; in addition, it will be assessed by measuring the beamforming gain achieved with our ML-REM based channel estimation algorithms versus a standard channel estimation approach that does not exploit such site-specific information.

Work plan: to achieve our proposed goals, we envision the following plan spanning a period of 10 months (43 weeks): Weeks 1-8: the grad student will familiarize with the massive MIMO capabilities of Powder, produce code to perform tasks such as beamforming, channel estimation, etc. These tasks can be executed remotely; Weeks 9-14: we will collect remotely propagation measurements using the massive MIMO functionalities of the testbed; these will be used to build a propagation map for channel prediction; Weeks 15-20: we will design algorithms to predict channel propagation conditions and use this information to design massive MIMO beamforming algorithms; we will run experiments on Powder to evaluate the effectiveness of these algorithms, using the success metrics outlined earlier; Weeks 21-24: a grad student will generate code to interface our mmWave measurement testbed with the Powder platform, using GNU Radio or Python; Weeks 25-32: the grad student will translate our beam-steering algorithms into a functioning system; Weeks 33-34: the grad student and one PI (Chris Anderson) will travel to the Powder testbed to deploy our equipment, perform mmWave experiments and collect propagation measurements; Weeks 35-43: the grad student will process the measurements and evaluate the success metrics discussed earlier. During this time, the student will also work on a manuscript to be submitted to a Journal, such as IEEE Transactions on Antennas and Propagation.

Justification of the need for supplemental funds

We plan to perform experiments on the PAWR Powder testbed, which is currently generally available. This platform provides state-of-the-art radio, compute, storage, and cloud resources, as well as the ability to work with existing hardware and software frameworks–or to build new ones from the ground up–and can be accessed remotely. These features will allow us to complement and enhance the research activities carried out in the existing project, as outlined next and in the summary of supplemental research activities.

Powder provides unique features, such as X310 USRPs with dedicated infrastructure and computing cluster, that provide 160 MHz of real-time bandwidth, and massive MIMO capabilities. These features will give us the opportunity to provide a proof-of-concept implementation of some of the core functionalities of the existing proposal, such as the multi-layer radio environment map (ML-REM) cloud-based platform used to store propagation measurements and perform channel prediction, and the location-based beam-steering algorithms. Further, our measurement campaigns to date have focused on suburban and rural environments; data collected from the Powder platform in an urban environment would be invaluable to our site-specific modeling efforts.