

White Paper: N.S.F.-F.C.C. Workshop on Tracking Quality of Experience in the Internet

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Scope of Relevant Current Research

My research relevant to quality of experience on the Internet factors into two main areas: indoor localization using phased array signal processing, and improving wireless access speed with MIMO.

Phased array signal processing has long been employed outdoors in radar, underwater in sonar, and underground in seismic monitoring. Today, it has the potential to revolutionize the Internet of Things (IoT) by giving us the ability to track every one of the billions of IoT devices indoors, and meet their exploding bandwidth requirements. But to make the shift to indoor wireless networks, it must cope with strong multipath radio reflections, packetized data transmissions, and commodity hardware platforms. *ArrayTrack* (USENIX NSDI '13) is the first indoor location service in the world to have achieved a median location accuracy of within 20 cm and sub-second responsiveness, without infrastructure beyond typical Wi-Fi access points. This has enabled the development of handheld route-finding and augmented reality applications not previously possible indoors. We have prototyped and evaluated *ArrayTrack* on a Wi-Fi radio platform and evaluated in a 50-node indoor wireless testbed situated in a real office working environment. Further work (Phaser, ACM MobiCom '13) resulted in a real-time *ArrayTrack* prototype on commodity Intel Wi-Fi hardware.

Geosphere is a physical- and link-layer design for multi-cell access point-based MIMO networks that consistently improves network throughput. To send multiple streams of data in a MIMO system, prior designs rely on a technique called zero-forcing, a way of “nulling” the interference between the different spatial streams by inverting the effect of the wireless channel matrix. In many cases, when this channel matrix is well-conditioned, zero-forcing is highly effective, eliminating inter-stream interference. But measurements from our indoor wireless testbed network indicate that many of its links suffer from poorly-conditioned MIMO channel matrices. In these situations, zero-forcing techniques leave performance on the table, so *Geosphere* uses sphere decoding that can make fewer errors, and therefore can realize more of the MIMO capacity. Results from our WARP testbed show that *Geosphere* achieves average throughput gains of 2× in 4 × 4 MIMO systems.

Relationship of Current Research with Quality of Experience on the Internet

We live in a world where wireless and mobile communications is a driving force. As industry and academia increasingly recognize its value, government has become increasingly open to tapping that value: thirty years ago, the F.C.C. opened up radio frequency bands at 900, 2400, and 5800 MHz to unlicensed data communication, and ever more frequent F.C.C. rulings have since established rules for operating in

the television “whitespace” frequency bands at 700 MHz, enabled operation in millimeter-wave bands at 24 and 60 GHz, and opened up more spectrum around already-established bands, such as 5 GHz.

As a result of the popularity of wireless, people use wireless to access the Internet in increasing frequency, in fact a full half of all networking devices will be mobile by the end of this year (Infonetics). In 2014, most businesses planned to increase Wi-Fi capacity by at least 20% (HP, Infonetics). At home, half of all PCs are now tablets, and 93% of all tablet owners will utilize Wi-Fi only (Deloitte).

Consequently, we must consider the impact of wireless on the Internet quality of experience. As part of this N.S.F.-F.C.C. workshop, I am interested in exploring ideas related to spectrum scanning in the busy wireless bands to determine whether and to what extent wireless bit errors are responsible for packet loss at the edge of the network, and whether packet losses that may be ascribed to wireless effects have a deleterious effect on network quality of service. This line of inquiry requires looking across the boundaries between the disciplines of computer networking and wireless digital communications. I therefore see an opportunity to contribute this kind of “cross-layer” thinking to the workshop.

The other line of my work on indoor localization is relevant because where users are can give us insight into areas that have poor Wi-Fi coverage and thus get a degraded Internet quality of service. Indoor localization can also estimate the mobility speed of users, another parameter that may be of use to studies on quality of service.