Proposal Overview

Collaborative Research: CNS Core: Medium: Scaling sub-THzWireless
Networks with Energy-Efficient Massive Holographic MIMO Arrays
(TeraMHM)

The available spectrum in the higher Millimeter-Wave (mmWave) and sub-Terahertz (THz) bands (i.e., from 100 to 300
GHz) has the potential to push the rate from today's Gigabits per second (Gbps) to Terabits per second (Tbps) enabling
new and emerging use cases [1–5]. However, ubiquitous Tb/sec connectivity faces several challenges. Specifically,
THz links suffer from higher path loss and molecular absorption resulting in a significantly limited communication
range [6, 7]. Adopting highly directional beams can alleviate this problem to some extent, yet, building large-scale
arrays within a reasonable power budget has remained the main challenge toward realizing wireless networks above
100 GHz. Our objective is to fundamentally advance today'ssub-THz networks by scaling them in range, adaptability,

and multi-user access. Via a combination of circuits, PHY layer, and link layer innovations, we will design, theo-
retically investigate, and experimentally evaluate the first sub-THz network where wireless nodes are quipped with

power-efficient massive MIMO sub-THz holographic arrays. Leveraging this unprecedented array structure, we pro-
pose a groundbreaking platform that mobile users, including smart phones, UAVs, cars, can establish and adapt highly

directional 100+ meter long links and achieve Tb/sec data rates.
Keywords: Wireless Networks; Sub-Terahertz WLANs; Holographic Array; Beamforming; LOS MIMO

Facilities, Equipment, and Other Resources (Princeton University)

Facilities. The PI’s research group has a recently renovated laboratory space on campus at Princeton University which is equipped with an optical table and several workstations. The lab has sufficient space and access to computers and the Internet for up to 10 students to work simultaneously. We have computing equipment available, including various desktop machines, laptops, and servers, that will support our experimental effort. In particular, we purchased a site license for CST, HFSS, and COMSOL multi-physics to run finite-element simulations on models with up to several million nodes. The Department of Electrical and Computer Engineering (ECE) at Princeton University has modern office space available for the PI, the co-PI, and their students. The PI receives administrative support from the department. Also, Princeton has modern networking equipment (both wired and wireless) deployed throughout.

Co-PI Sengupta has all an extensive electronic measurement facility in his lab along with optical measurement capability including free-standing optical Table, multiple laser sources, optical power measurement capability, filters, mechanical positioners and manipulators. The entire electrical and optical characterization can be performed in the PI’s lab. In addition, the PI has access to the PRISM Micro/Nano Fabrication Lab (MNFL), and the Imaging and Analysis Center (IAC). The MFNL and the IAC are operated by the Princeton Institute for the Science and Technology of Materials (PRISM) and are open to all in the Princeton community.

Equipment. PI Ghasempour and co-PIs Sengupta and Rangan collectively have all the equipment that will be used to build and evaluate the proposed research (DC-to-THz). These include several systems for ultra-broadband characterization of components and for scale-model network experiments. We use terahertz time-domain spectrometers, with fiber-coupled transmitter and receiver antennas, to generate and detect ultra-broadband (100 – 2000 GHz) transients. Both amplitude and phase information can be obtained at all frequencies within this bandwidth. These systems provide excellent dynamic range for broadbandmeasurements, although with somewhat limited spectral resolution (e.g., about 1 GHz) and with no ability to modulate the signals.

Furthermore, at Princeton University, we have the following measurement equipment: (i) Vector network analysis capability till 125 GHz (recently expanding to 500 GHz), (ii) Banded waveguide-based signal generation and detection capability till 1.2 THz; (iii) Multiple 65 GS/s Keysight Arbitrary waveform generator; (iv) Multiple mmWave signal generators; (v) multiple spectrum analyzer with measurement capability up to 750 GHz, (vi), multiple 80+ GSa/s real-time oscilloscopes, (vii) Various RF components such as amplifiers, mixers, attenuators, VCOs, filters, bias tees, power splitters, DC bias, hybrids, directional couplers, and isolators, coaxial cables. and waveguide components.

Other Resources. Several Linux workstations and server machines with industrial CAD software for the design for design of RF, mm-Wave and sub-mmWave ICs (Cadence, Mentor tools, Agilent Advanced Design Systems (ADS), Ansoft HFSS, Labview) along with computational tools such as MATLAB with its accompanying communication packages etc. One personalized computational server for Lab including a 128 core processor and 500 GB RAM. Finally, the Princeton Library system houses over eleven million holdings including digital subscriptions to journals relevant to the research proposed. The PI also has the support of Princeton's Office of Technology Licensing for all issues relating to inventions, patent applications, and licensing should the need arise.

Facilities at NYU WIRELESS

The NYU WIRELESS Center is located on the 9th floor of 2 Metrotech Center on the Brooklyn campus of the university. Laboratory space for this project will be performed in one of two rooms with specialized equipment for RF propagation measurements and baseband prototyping. The center also provides modern office space for over 40 students and 6 faculty.
The labs for this project are managed by Prof. Rangan, who has over fifteen years of experience
in commercial cellular design, both at a startup and Qualcomm. The laboratory has significant tools for the design, implementation, and study of mmWave wireless signaling, protocols and sensing
in real environment. In order to get the greatest flexibility and scale of deployment, the testbed equipment in a modular fashion, involving the following hardware components, largely provided by
the industrial affiliate National Instruments:

- NI PXIe 1082 chassis (2)
- NI PXIe 8133 Real-Time Controller (2)
- NI 7965 FPGA boards based on Xilinx Virtex-5 (4)
- NI 7966 FPGA boards based on Xilinx Xirtex-5 (4)
- NI 7976 FPGA board based on Xilinx Kintek-7 (1)
- NI 5781 FlexRIO Adaptor module (4)
- NI 5791 FlexRIO Adaptor module (2)
- Multi-core desktop PCs (4)
- Sivers IMA mmW V-band module for 57-63GHz communication (2)
- FLIR D-48 mechanically steerable gimbals (2) with tripod mounts of various sizes. This can be used for mechanical directional scanning and simulation of rotational motion.
- SiBeam 12x5 element phased array transceiver module (2).

The SiBeam phased array system is one of the few such systems at universities. It is has two 12x5
arrays (one for TX and one for RX) with a maximum of 23 dBi gain and a horizontal steerable range
of ± 30 degrees. In addition, we have hardware that includes a spectrum analyzer, oscilloscope, arbitrary function generator, various antennas and associated test components.
The powerful testbed is capable of building and prototyping end-to-end systems, involving all layers of the protocol stack. It can also be used for high performance mmWave sensing. Importantly,
the computational power in the components is sufficient to test many of the very high data rate, wide bandwidth aspects of mmWave communication and sensing.
PHY layer baseband and signal processing can be implemented on the various FPGA boards, in
order to support high bandwidths. The FPGA boards are programmed using the LabView FPGA module, and the Xilinx platform is used to compile the FPGA bitfiles. The powerful Virtex-5 and Kintek-7 FPGA boards have the resources to support complex PHY protocols and have already been showcased in various high profile mmWave demos. Much of the code to support this project

has already been developed. The baseband signals from the FPGA boards can be converted to IF (carrier frequency of up to 4.4GHz) by the NI 5791 module. These can be directly sent out over antennas, or can be further up-converted to millimeter wave signals in the V-band using the Sivers IMA modules or the SiBeam 12 element phased array. The interface is flexible and we can easily adapt the module to interface with a prototype ADC / DAC chips.