RF-to-THz Communication and Sensing: Opportunities and Research Challenges

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***Abstract*— We describe the opportunities, and the research challenges, presented in the development of 0.1-1THz wireless communications and imaging systems. In THz communications links, short wavelengths permit massive spatial multiplexing both for network nodes and point-point links. THz imaging systems can provide TV-like resolution from small apertures, supporting foul-weather driving and aviation.**

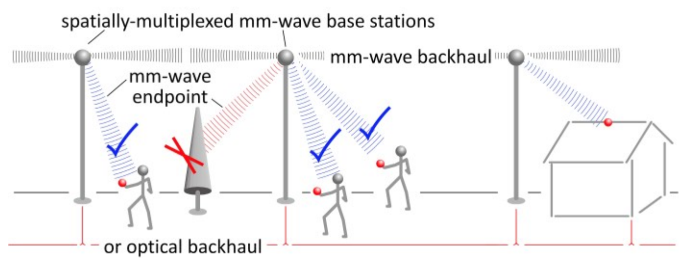
Keywords—mm-waves, THz, RADAR, imaging. RF-wireless systems.

I. INTRODUCTION

The RF bands below ~5GHz have supported explosive growth in mobile communications. Demand has grown quickly, and will soon outstrip the available wireless spectrum. In response, the industry is now poised to move to 5G systems, with carriers at 28, 38, 57-71(WiGig), and 71-86GHz. Research now explores the next generation of wireless systems, these operating between 100GHz and 1THz. For brevity, we will refer to these as THz systems [1].

THz frequencies will be exploited for multi-Gigabit mobile communication, providing high capacity access to data from almost any location (Figure 1a). Base stations (network hubs) will provide spatially-multiplexed mm-wave endpoint (user) connections, with network backhaul on a mix of optical fiber and high-capacity mm-wave links. In a convergence of cellular and internet services, similar networks will provide high-capacity residential/office communication, providing competition, low cost, and broad distribution of cloud data, streaming video, videoconferencing, internet, and telephone.

These bands will be exploited in transportation (Figure 1b), supporting self-driving cars and intelligent highways. Sub-mm-wave imaging radar, at ~340GHz or above, can provide HDTV-resolution to see through fog and rain. Coupled with a heads-up display, this will assist drivers, allowing one to drive safely in fog at 100 km/hr. Such imaging radar would complement LIDAR in self-driving cars, working in bad weather and good. Fast mm-wave links would provide links between cars and highway traffic control, coordinating traffic, anticipating and managing interactions, and avoiding collisions.



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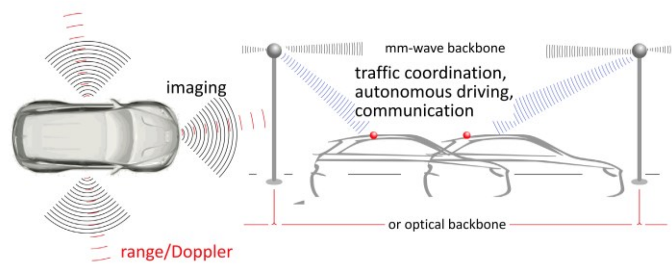

(b)

Figure 1: mm-wave/THz applications: (a) spatially multiplexed networks for multi-Gigabit mobile and residential/office communication and (b) THz radar and imaging systems supporting autonomous cars and driving in foul weather, with wideband links between cars and highway infrastructure to coordinate traffic.

These bands will support sensing/imaging for aviation and for national security, identifying threats through fog/smoke/dust, when one cannot see in the optical. Microwave radar provides longer range but lower resolution, detecting threats at long-range. 140-400GHz imaging radar will be for threat identification, providing shorter range (~500m in fog), but TV- or HDTV-like resolution, even from a small aperture which can fit on a jeep, helicopter, or UAV.

II. THZ SYSTEMS

THz wireless systems can provide very high data capacity. In clear weather, there are large bandwidths at 125-165GHz and 200-300 GHz between absorption lines, and narrower windows at 340, 650, 850, and 1080GHz. The short wavelengths support massive spatial multiplexing; a phased array with MIMO processing (Figure 2a) can, within a shared bandwidth, form multiple, independent signal beams, carrying

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independent modulation. The angular resolution is $\lambda/(\text{array width})$, and there can be as many signal beams as there are array elements. At 140 and 220GHz, we anticipate systems with capacity approaching 1000 beams and 1Tb/s aggregate data rate, supporting ~200m range. Line-of-sight MIMO (Figure 2b) uses similar array techniques for massive spatial multiplexing in point-point links. On 250m links, using 340 or 650GHz carriers, we envision capacities approaching 1Tb/s. In imaging (Figure 2c), given $\lambda/(\text{aperture width})$ beamwidth, THz frequencies provide sharp angular resolution and massive numbers of pixels from small apertures.

III. THz Challenges

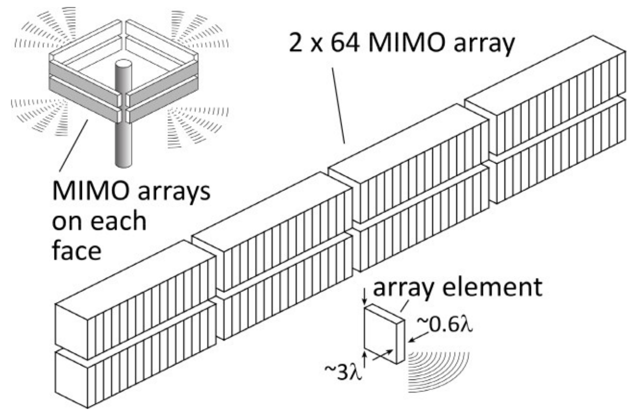
There are profound challenges. Propagation loss is severe, both from λ^2/R^2 propagation losses and foul weather attenuation of even 30+ dB/km. Given the small wavelengths, beams are easily blocked. Phased array transceivers are necessary for adequate transmission range (given the necessary small beam width, fix-aimed antennas are expensive to install) and to provide *adaptive beam steering* in *mesh networks* to accommodate beam blockage.

The electronics is a challenge: CMOS works well to 220GHz but struggles at higher frequencies; we envision THz GaN and InP transistors to extend to 340GHz and beyond. Longer ranges and hundreds of beams strain the link budget; we envision massive arrays and/or high-power GaN PAs and sensitive InP LNAs to extend range. Array packaging is formidable, with 100's of THz signal connections, at times extreme power densities, and, with small wavelengths forcing small element spacings, little space to fit RF channels.

Massive MIMO challenges the entire transceiver chain: dynamic range must be high, and the beamformer must have high resolution. We envision a mix of RF, IF baseband analog, and baseband digital beamforming. Given high symbol rates and large delay spreads, equalizing multipath interference could be formidable. We envision a mix of analog and digital equalization. Multipath can also be suppressed by array null-forming, with diminishing SNR penalty given very large arrays. Large arrays, useful for link gain and multipath suppression, suffer poor modulation bandwidths; true-time-delay, at the tile level, or array frequency channelization, are means to address this.

At the system level, the THz radio channel must be modeled, addressing attenuation, beam blockage and partial shadowing, and multipath fading and ISI. Given the complexity of massive MIMO, a systematic understanding of the transceiver dynamic range must guide the hardware architectural design. Networking is a challenge; it is difficult to quickly establish communication between highly directional transmitters and receivers, and we seek to develop compressive sensing algorithms for beam tracking. Further, given the high data rates, and high rates of beam blockage driving frequent network re-routing, fast adaptive network protocols are needed to maintain high data transmission rates.

In imaging, THz systems provide high angular resolution, but, a phased-array imager requires as many RF transceiver channels as there are image pixels; this is a formidable requirement given that the angular resolution can permit $\sim 10^6$ pixels. Hardware (frequency scanning) and software approaches (compressive imaging) can reduce to manageable levels the required number of RF channels.



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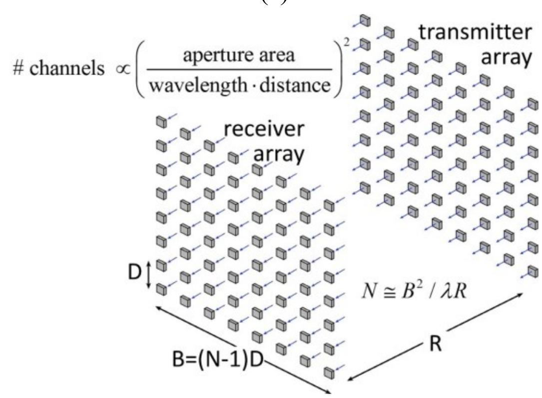

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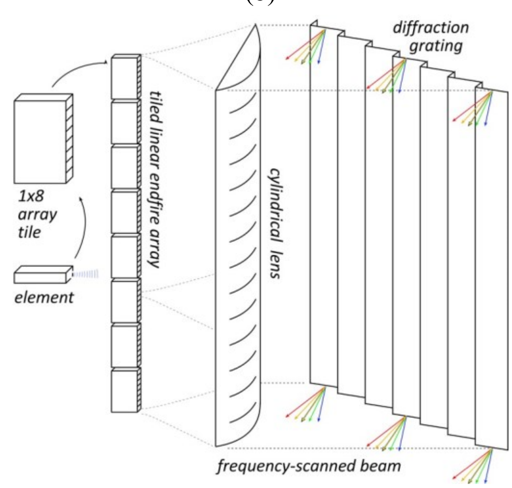

(c)

Figure 2: (a) Phased-array beam steering in a network base station for multiple independent beams at a given carrier frequency. (b) Spatial multiplexing in a line-of-sight mm-wave MIMO link, with the capacity varying as the product of the channel bandwidth and the square of the carrier frequency. (c) A high-resolution THz imaging radar system, using array phase-shifting and frequency-scanning to steer in altitude and azimuth.

[1] 30-300GHz is mm-wave; 0.3-3THz is sub-mm-wave..