Millimeter wave communication: From Origins to Disruptive Applications

Professor Robert W. Heath Jr.

Situation Aware Vehicular Engineering Systems
Wireless Networking and Communications Group
Department of Electrical and Computer Engineering
The University of Texas at Austin

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Introduction
Cellular networks are connecting everyone (wirelessly)
Future networks will connect things beyond people

- Vehicles
- Offices
- Homes
- Factories
- Cities
- Drones
Wireless communication

Wireless systems send information using radio frequency signals
Frequency and wavelength

Wireless communication occurs and different frequencies

- High Frequency (HF)
  - Amateur radio
- Ultra High Frequency (UHF)
  - Cellular signals
- Millimeter Wave
  - mmWave
  - WiFi
Bandwidth is the basic resource in a communication system.

Information rides on fluctuations of the carrier.

Fluctuations carry different frequencies.

More rapid fluctuations consume more bandwidth.

Less fluctuations, lower bandwidth.

More fluctuations, higher bandwidth.

Power

BANDWIDTH

carrier

frequency
The higher the bandwidth, the higher the data rate the system can achieve.
Wireless systems can also exploit multiple antennas

MIMO: Multiple Input Multiple Output

Multiple antennas enable transmission of several parallel data streams using the same frequency resources

MIMO spatial multiplexing makes better use of bandwidth
What influences the rate experienced by a user?

rate per user = \frac{\text{bandwidth} \times \text{MIMO}}{\# \text{ of users}} \times \text{spectral efficiency}

MIMO spatial multiplexing gain depends on the number of antennas in the system.

Bandwidth is the easiest leverage for higher data rates.

Claude Shannon
Inventor of Information Theory

H = -\sum p(x) \log p(x)
Millimeter wave spectrum

Spectra below 3 GHz is packed and $$/Hz of bandwidth is huge

Lots of potential spectrum available at mmWave for consumer applications currently used for backhaul or legacy systems
First millimeter wave experiments

Transmitter antennas

* Pictures from D. T. Emerson, “The work of Jagadis Chandra Bose: 100 years of millimeter-wave research”, IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 45, NO. 12, DECEMBER 1997

Radiation receiver

First mmWave experiments were undertaken more than 100 years ago!
Millimeter wave band uses

MmWave has a long history in sensing and communication

1895
Bose experiments

1944
SCR-584
Fire control radar

1970
Atacama millimeter wave array (Chile)
Radio astronomy

2009
2014
2001 Mars Odyssey
Satellite-based remote sensing
Satellite links
Security screening
Backhaul
WirelessHD*
WiFI IEEE 802.11ad

MmWave has just now reached consumer applications

Until recently, mmWave devices were expensive, bulky, or made with expensive semiconductor processes.
Consumer challenge #2: propagation effects

Penetration loss

Scattering

More scatterers but fewer paths

Direct path blocked

Diffraction not significant

Propagation has not been well understood by systems engineers
Consumer challenge #3: antennas become too small

Small antennas do not capture as much of the impinging wave.
Making mmWave viable for consumers
Idea 1: An antenna array at the receiver fixes shrinkage

Large antenna array captures the same amount of energy avoiding the misconception that losses increase with frequencies.
Idea 2: An antenna array at the transmitter focuses energy

Beamforming at the transmitter adds additional array gain and reduces caused interference.
The antenna arrays are small at mmWave

Antennas are about 10 mm

16-element array 1 (the large objects are antenna connectors, used only for prototyping)

Base station may have 64 to 512 antennas

Mobile station may have 4 to 32 antennas

Idea 3: Analog processing

Forming beams using analog components reduces the amount of RF hardware and subsequent baseband processing required.
Idea 4: Beam training

TX sends training sectors on each RX sector

Antennas need to be adaptively pointed

Beam training finds the best beam pair over the air
Commercial mmWave applications

Current standards for personal networks and WiFi support arrays and beam training

<table>
<thead>
<tr>
<th>Standard</th>
<th>Bandwidth</th>
<th>Rates</th>
<th>Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>WirelessHD 1.1</td>
<td>2.16 GHz</td>
<td>4 x 7.138 Gbps</td>
<td>Jan. 2010</td>
</tr>
<tr>
<td>IEEE 802.11ad</td>
<td>2.16 GHz</td>
<td>6.76 Gbps</td>
<td>Dec. 2012</td>
</tr>
</tbody>
</table>

* http://www.wirelesshd.org/consumers/product-listing/
Bringing mmWave to 5G and beyond
Taking advantage of MIMO processing

Hybrid precoding enables multi stream transmission with low power, but requires changes in conventional MIMO algorithms.
Reducing resolution in data converters

Higher levels of quantization dramatically reduce power consumption, but require new algorithms that can deal with extra distortion.
Overcoming different types of blockage

- Secondary reflectors, multiple paths, and active reflectors
- Dense deployment of infrastructure and fast switching
- Handset antenna diversity, warning signs, and electric shock
Alternatives to conventional beam training

Simultaneously sampling from multiple spatial directions

Exploit the fact that there are a few good paths via compressive sensing
Adaptive reconfiguration in high mobility

Leverage out-of-band information, multi-band communication, position, sensors, and machine learning to reduce overheads during beam reconfiguration
Disruptive applications
5G cellular networks will exploit mmWave

Fixed wireless access

Vehicle-to-X

Air-to-X

Robots

Wireless backhaul

UE

Backhaul

5G @ mmWave will provide high data rate connectivity for different types of applications
Vehicle-to-everything (V2X) communication

- Full automated driving
- Cloud assisted driving
- Traffic efficiency
- Cooperative collision avoidance
- Intelligent navigation
- Information society on the road

High data rate connectivity is relevant for the automotive industry

Low latency and Gbps data rates are not supported
Communications for aerial vehicles

- Sensor fusion in disaster areas
- Mobile cellular infrastructure
- Ambulance drone
- Panoramic VR streaming of live video
- Communications relay
- Safe navigation for package delivery
- Factory inspection, pipeline monitoring

High data rate networking between manned and unmanned aerial vehicles enables revolutionary applications. Current solutions for A2X do not support most applications.
People (going beyond smart phones)

Virtual reality: high-resolution multi-view video in real-time

Wearable networks: multiple communicating devices in and around the body (>5 according to market trends)

Augmented reality: real-time overlay of information

High data rates are required for virtual and augmented reality and wearable networks
Connected robots

- Video cameras
- 3D image sensor
- IR camera
- Inertial motion sensor
- Laser scanner
- Sonar
- Radar
- Pressure sensor
- Central unit
- Tactile sensor
MmWave communication prototyping

State of the art research platform

Phased array platforms

Sensors and communication equipment for V2X

Quanergy M8 Lidar

High precision GPS

Cohda Wireless DSRC

Area Scan Cameras

RSU

Delphi Radar

Three different type vehicles

Questions?

www.profheath.org
www.utsaves.org
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