Antennas and System for Emerging 5G Communications

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In 10 to 20 Years…

Forget About This:

Remember This...:

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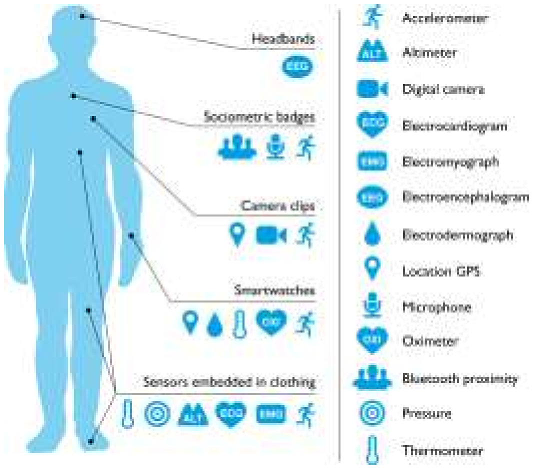
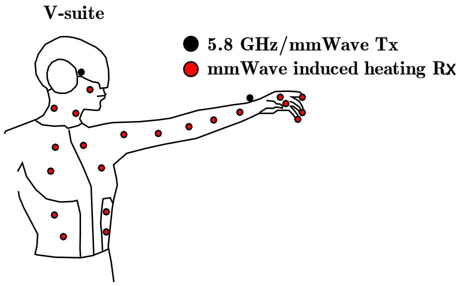
…and These





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Overview on 5G

ITU-R has defined three main types of usage scenarios that 5G is expected to enable:

- Ultra Reliable Low Latency Communications (URLLC),
- Massive Machine Type Communications (mMTC),
- Enhanced Mobile Broadband (eMBB), refers to using 5G as an evolution to 4G LTE mobile broadband services with faster connection, higher throughput and more capacity.

Frequency ranges:

- Existing LTE frequency range* (600 MHz to 6 GHz)
- mmWave bands** (24-86 GHz)

* In Sub 6-GHz bands, 5G is **evolutionary** since it will not diverge architecturally from existing LTE 4G infrastructure. At this band, LTE max modulation format is 128 QAM, while in sub-6 GHz 5G a modulation format at **256 QAM** is supported resulting in a significant throughput improvement at sub-6 GHz bands. Nevertheless, **LTE-Advanced already uses 256 QAM**.

** Promising bands: 28–30 GHz, the license-free band at 60 GHz, and the E-band at 71–76 GHz, 81–86 GHz, and 92–95 GHz. At 60 GHz band, different spectra are allocated depending on countries (e.g. 57 –66 GHz in Europe, 57 –64 GHz in North America and South Korea, 59.4–62.9 GHz in Australia, 59–66 GHz in Japan)

Overview on 5G

5G Launches in the US:

- AT&T: mmWave commercial deployments in 2018 (28/39 GHz for **fixed wireless**)
- Verizon: 5G **fixed wireless** at 28 GHz in four U.S. cities and mmWave deployments
- Sprint: **mobile** 2.5 GHz band for 5G
- T-Mobile: **mobile** 600 MHz for 5G in 30 cities

Applications

- WLAN and **high speed wearable** (WBAN) devices connected to cell phones, smart watches, augmented reality glasses and virtual reality headsets operating at 60 GHz could be **the first widely deployed consumer wireless devices at mmWave**.
- Since mmWave are already used for automotive radars, they could play a key role in developing **connected autonomous cars**

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Requirements for 5G

- ***Latency****:* current 4G technology latencies are on the order of **15 ms**. Two-way gaming, tactile internet, virtual and enhanced realities will need 5G to support a **roundtrip latency of 1 ms**;
- ***Data rates***: **peak** data rates of **20 Gbps** and **1 Gbps experienced by the user**. That is, 1000X or 100X the current 4G technology;
- ***Energy and costs***: the **same energy efficiency of 4G** is expected. Ideally, energy consumption should be reduced. Since it is expected a per-link data rate increase by about 100X, a Joules per bit and cost per bit will need to fall by 100X, at least.

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Effects of Low Latency

- Youtube Video

Ericsson 5G: 19 milliseconds can change everything

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High Data Rates

The need for **higher data rates (20 Gbps)** gets more attention. Achievable through:

- More active nodes per unit area. That is: **more cells**;
- **Increased bandwidth**. Achievable by both moving into the mmWave spectrum and making better use of WiFi's unlicensed spectrum in the 5-GHz band;
- **Spectral efficiency** 3x to 4x than 4G to support more **bits/s/Hz**. Achievable my using advanced **MIMO** architectures.

High Data Rates – More Cells

The first generation of cells, in the early **1980s**, had cell sizes of **hundreds of square km**. **Nowadays**, in Japan, the spacing between base stations can be as small as two hundred meters, corresponding to a cell size **under the tenth of square km**.

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High Data Rates – Increased Bandwidth

- **Atmospheric and rain absorption**: **oxygen** absorption is **15 dB/km @ 60 GHz** band but, for short-range indoor links and in the urban cellular deployments where the BS spacing is of the order of 200 m, this is **inconsequential**. Absorption is actually beneficial to **reduce interference** from more distant BSs.

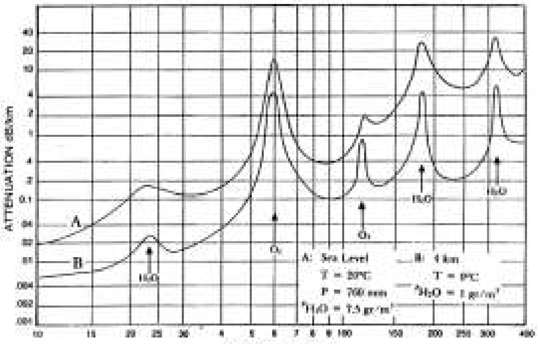


Figure 4: **Average Atmospheric Absorption of Millimeter Waves.**

High Data Rates – Increased Bandwidth

Blockage: as the transmit-receive distance grows, the **pathloss** drops to **40 dB/decade** plus additional **blocking loss** of **15-40 dB** in NLoS.

- A brick can attenuate mmWave signals by 40 to 80 dB;
- the human body itself can result in 20 to 35 dB loss;
- foliage loss can also be significant.

the human body and most building materials are reflective. This allows to be to enable coverage via NLOS paths. Because of blocking, a link can transition from **usable** to **unusable -->** interference is **de-emphasized** and the wide BW make them **noise-limited** (rather than interference-limited like in 4G).

High Data Rates – Increased Bandwidth

- **Propagation Loss**:

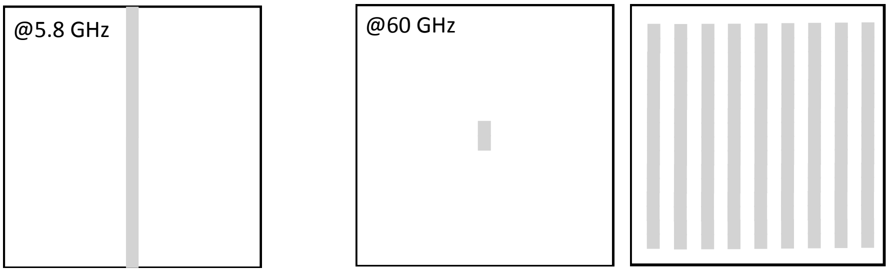
Broadcast communications: $P_r = G_t G_r \left(\frac{\lambda_c}{4\pi r}\right)^2 P_t$

If both the transmit and receive antenna apertures are held constant, then the free-space **path loss diminishes** with f_c^2

Point to point communications: $G = A\left(\frac{4\pi}{\lambda_c{}^2}\right)$ $P_r = A_t A_r \left(\frac{1}{\lambda_c r}\right)^2 P_t$

However, if the antenna aperture is **kept constant** at one end of the link as the frequency increases, the free-space path loss remains **unchanged.**
If both the transmit and receive antenna apertures are held constant, then the free-space **path loss diminishes** with f_c^2

High Data Rates – Increased Bandwidth



$$P_r = A_t A_r \left(\frac{1}{\lambda_c r}\right)^2 P_t$$

- 🙂 This is possible with antenna arrays. mmWave array sizes examples: 16 or 256 elements. It can be higher. IEEE 802.11ad products with 32 elements are already available.
- 😐 The challenge is to cophase many antennas in a rapidly changing channel due to mobility, blocking, and changing in device orientation.
- 🙁 The costs and power consumption of ADC and DAC converters operating at wide bandwidths are high

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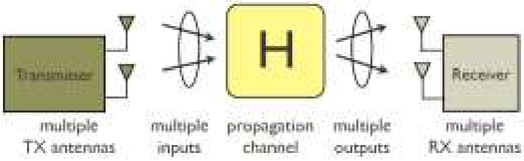
High Data Rates – MIMO

MIMO systems allow ***spatial data multiplexing****. In these schemes,* ***multiple parallel data streams are transmitted simultaneously*** *and* ***in the same frequency band*** *and can be separated at the receiver.*




Stream data to multiple devices simultaneously

MIMO is **used** in commercial WLAN (IEEE 802.11n/ac) and cellular (IEEE 802.16e/m, 3GPP cellular LTE and LTE Advanced) systems **at sub-6 GHz frequencies**. They support **up to 8 antennas**. **Two are common**.
Arrays at mmWave can have more elements: 32 to 256 elements are common.

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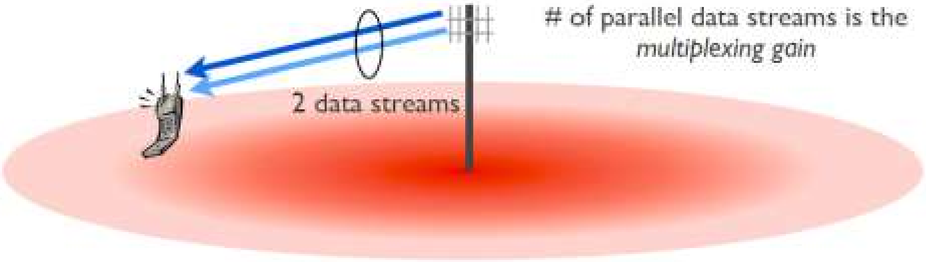
High Data Rates – MIMO

Single-user MIMO (SU-MIMO): sends multiple data streams to a single user. The spatial dimensions are limited by the number of antennas that can be accommodated on a mobile device



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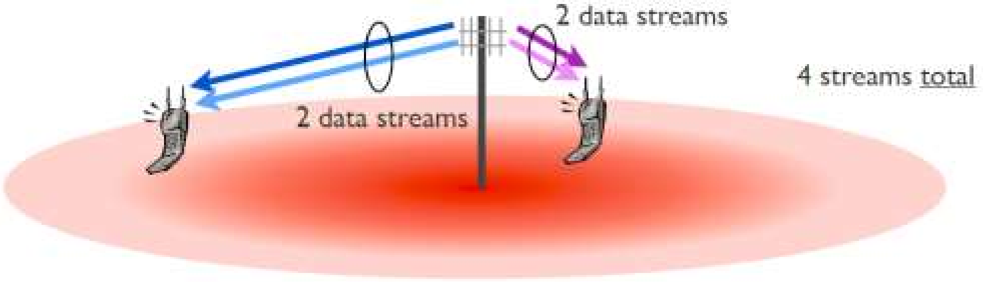
High Data Rates – MIMO

Multi-user MIMO (MU-MIMO): when each BS sends multiple data streams to several users concurrently



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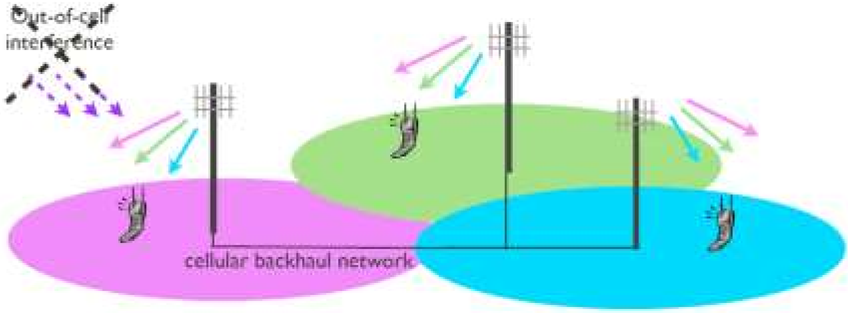
High Data Rates – MIMO

Coordinated multipoint (CoMP): BSs can cooperate and act as a single effective MIMO transceiver turning interference into useful signal



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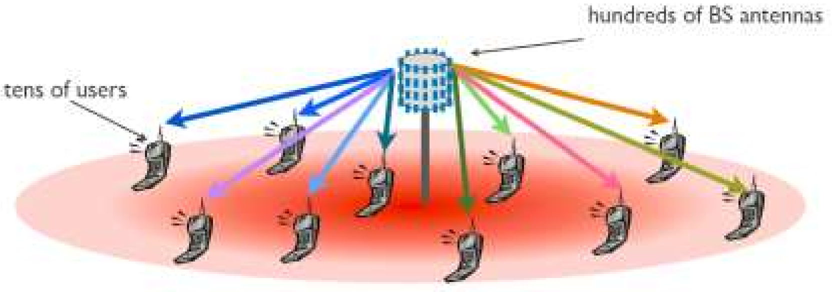
High Data Rates – MIMO

Proposed in 2007 by Marzetta (Bell Labs), named **large-scale antenna systems**, now known as **massive MIMO**. Equip BSs with a number of antennas (hundreds) much larger than the number of active users. Many users are served simultaneously.



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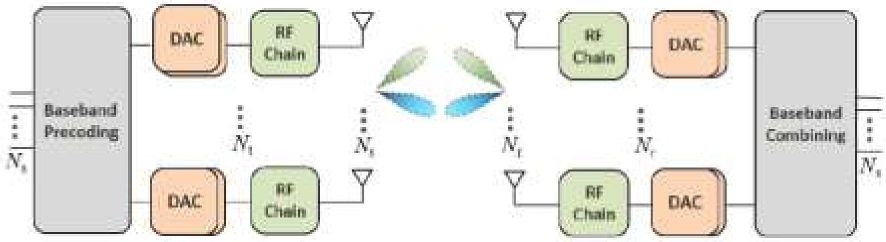
High Data Rates – MIMO

MIMO, at **lower frequencies**, is an exercise in digital signal processing taking place at baseband.



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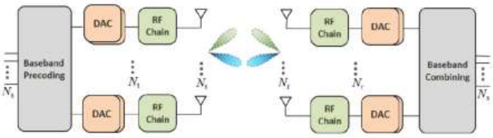
High Data Rates – MIMO



At **higher frequencies** and **higher BWs**, hardware constraints make it difficult to have a separate RF chain (PAs, LNAs, VCOs) and data converter for each antenna:

i) the RF connections of PAs or LNAs to each antenna element and all baseband connections are very difficult at mmWave. These devices have to be packed behind each antenna, very close to each other;
ii) PAs, ADCs, … are power hungry at mmWave;
iii) digital conversion stage per antenna needs a large demand on digital signal processing, since many parallel GSps data streams have to be processed

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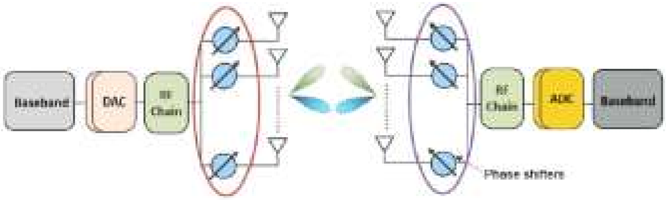
MIMO - Analog MIMO



Analog beamforming (supported in IEEE 802.11ad) is one of the **simplest approaches** for applying MIMO in mmWave systems

Often implemented using a network of **digitally controlled phase shifters**. Each antenna element is connected via phase shifters to a single RF chain.

Performance are **limited** by the use of **quantized phase shifts** and the **lack** of **amplitude adjustments**. This makes more challenging to finely tune the beams and steer nulls. **High # of phase shifters** and **high power consumption** are also a concern

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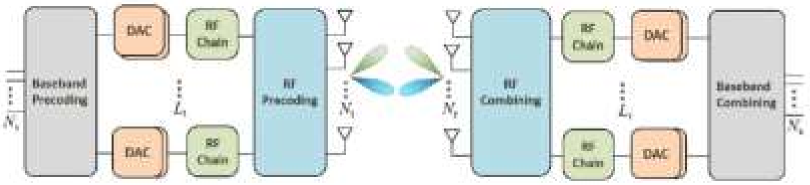
MIMO – Hybrid MIMO

Hybrid architectures can provide enhanced benefits of MIMO communication at mmWave frequencies by **dividing the MIMO process between analog and digital domains**.



MIMO – Hybrid MIMO

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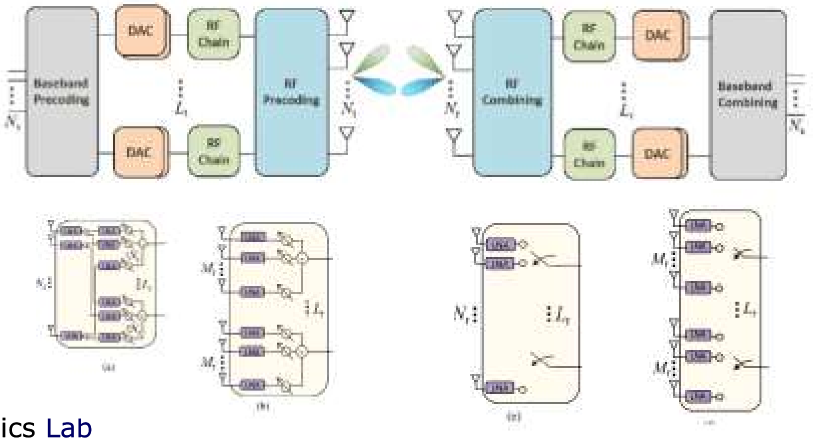
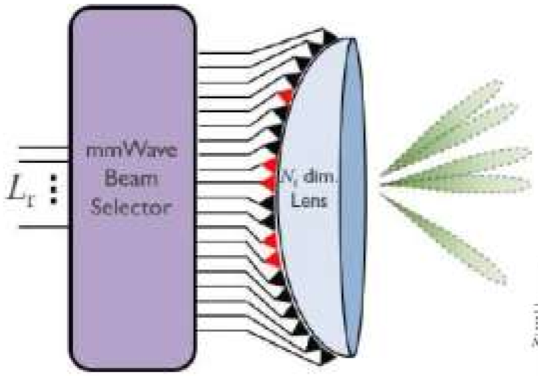
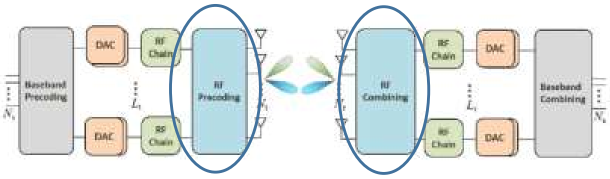


Continuous Aperture Phased- (CAP-) MIMO

Another, low complexity, hybrid architecture uses a **lens antenna** at the front-end for analog beamforming.

The antennas and RF precoder/combiner are replaced by the continuous aperture lens antenna. A mmWave beam selector directly samples via an array of feed antennas arranged on the focal surface of the lens antenna





Summary

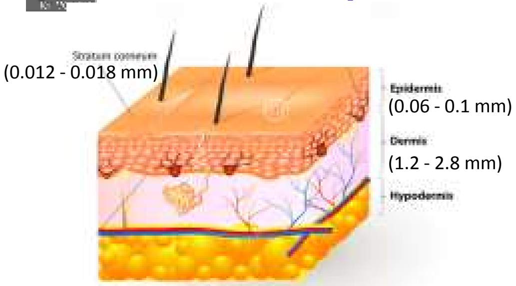
Aim of 5G is to achieve:

low latencies (1 ms); low power consumptions; high data rates (peaks 20 Gbps)

Efforts are focused on **increasing data rates**. Possible through:

- more cells,
- more bandwidth (optimized sub-6 GHz spectrum and use of mmWave bands);
  - Absorption → not a problem with 200 m cell radius;
  - Blockage → makes 5G noise-limited;
  - Propagation Losses → overcome with beamforming
- more spectral efficiency (more bit/s/Hz)
  - Massive MIMO → complex and expensive systems
    - Analog MIMO
    - Hybrid MIMO
    - CAP-MIMO

Skin Properties and Heating



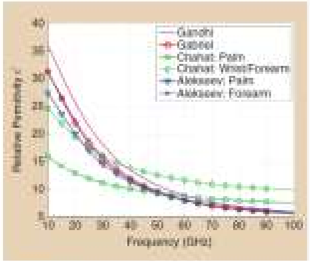
Stratum corneum: **low water content** (15-40%) Total water concentration in the **rest** of the epidermis and dermis is **70-80%**.

The **high water** content leads to **high absorption** coefficients at mmWave. Thus, energy:

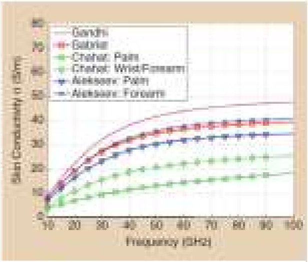
- penetrates the stratum corneum;
- is rapidly absorbed within the epidermis and dermis;
- does not propagate further into the body.

Established **permittivity database** is **missing** for mmWaves

Researchers **extrapolated** complex permittivity of human skin at mmWave band from experimental data available at uWave frequencies; others have conducted **direct measurements** for characterization of the human skin



Relative Permittivity



Conductivity

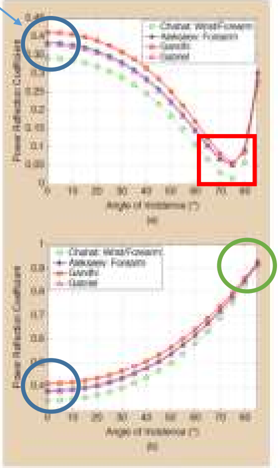
*Further measurements of different **body sites** and **human subjects** are **needed** for developing accurate models.*

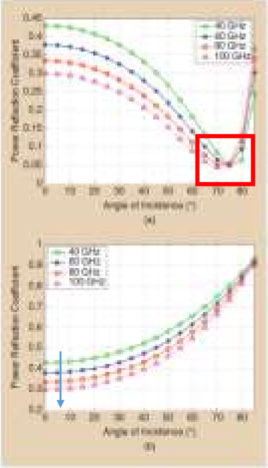
Skin Properties and Heating

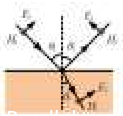
Parallel *vs* perpendicular polarizations

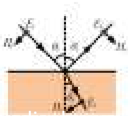
30-40% of incident normal power is **reflected** at the skin surface

to ***minimize*** *on-body channel loss,* ***polarization perpendicular*** *to the body surface is preferred*






Parallel pol.


Perpendicular pol.

Brewster angles of 60^o to 80^o at various frequencies 🟥

43% of the incident normal power is reflected at the skin @40 GHz power reflection coefficient decreases to 30% @100 GHz

More *power is transmitted* ***into*** *the body at* ***higher*** *freq.*

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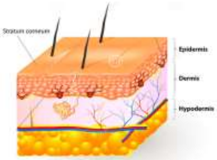
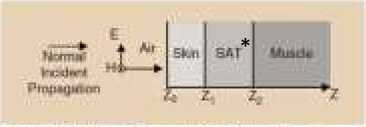
Skin penetration





A 1-D three-layer human tissue

* subcutaneous adipose tissue

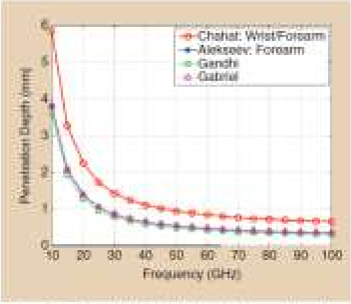


Figure 6. *The penetration depth in the human skin with the increase of exposure frequency.*

skin models show that **penetration depth** decreases with the increase of frequency

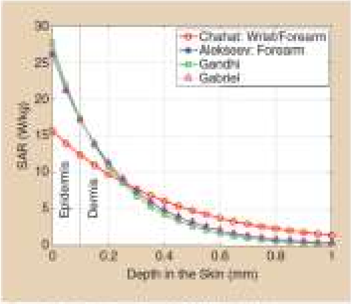
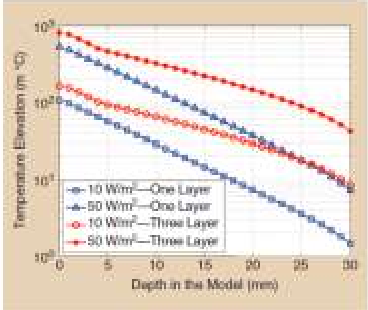


Figure 7. *The attenuation of SAR in the skin for an incident PD of 10 W/m² at 60 GHz.*

> 90% of the tx power is **absorbed** within the epidermis and dermis



Simulations show that a 1-layer skin model gives **different results** from a 3-layer skin model

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***Accurate** human body models are needed to predict the **temperature elevation** for safety assessments due to mmW radiation.*

Other mmWave Effects

- Attenuation of most **garment materials** is negligible: **<3 dB** below 350 GHz
- Clothing in direct contact with skin can act as **impedance transformer** enhancing power transmission into the body. **Air gap** of up to **2 mm** between clothes and skin decreases the body transmission
- mmWaves could activate **natural kill (NK) cells** that remove tumor cells;
- mmWaves might **accelerate healing of wounds** and heal wounded skin without leaving scars*
- mmWave are **not genotoxic** (i.e.: they do not induce cancer)
- **Eyes are vulnerable** to mmWave radiation-induced heating as they lack sufficient blood flow to redistribute the generated heat;
- **membranes might be affected** by mmWaves at PD levels typically expected from wireless communication systems (0.9 mW/cm2)
- **Long-term effects of heating** due to mmWave frequencies are **unknown**

*Several beauty clinics in the former Soviet Union used mmWave therapy in cosmetology

Summary

Skin

- ***Accurate*** *human body models are needed to predict the* ***temperature elevation*** *for safety assessments due to mmW radiation*
- *Further measurements of different* ***body sites*** *and* ***human subjects*** *are* ***needed*** *for developing accurate models*

Practical

- *To* ***minimize*** *on-body channel loss,* ***polarization perpendicular*** *to the body surface is preferred*
- *Clothing in direct contact with skin can act as* ***impedance transformer*** *enhancing power transmission into the body.* ***Air gap*** *of up to* ***2 mm*** *between clothes and skin* ***decreases the body transmission***
- Attenuation of most **garment materials** is negligible: **<3 dB** below 350 GHz

Wireless Telesurgery & Service Robots

- **Reaction times** of 100 ms, 10 ms, and 1 ms required for auditory, visual, and manual interaction, respectively, so that **all human senses can interact with machines**, hear and see things remotely

- **Service robots** for care will join the labor force with logistic, cleaning, and monitoring roles. Robots will also need interpret human emotions, interact with people, and assist patients and old people in hospitals

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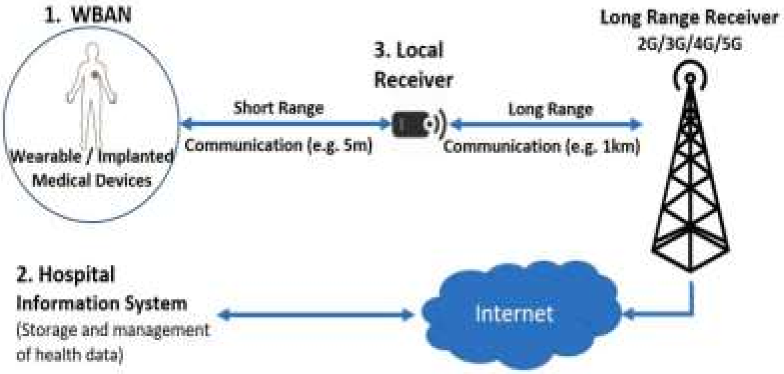
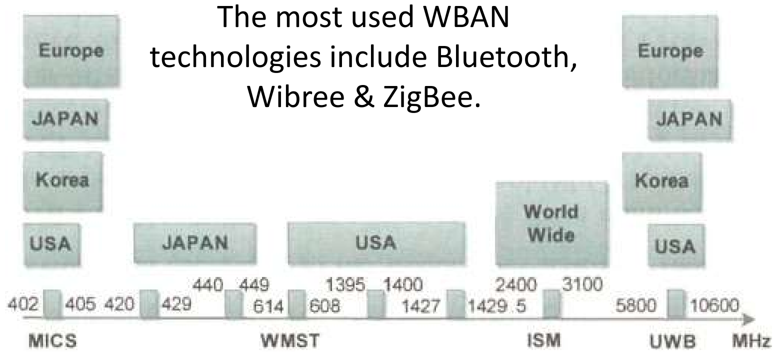
Wireless Body Area Networks (WBANs)



Requirements: reliability, quality of service (QoS), low power, data rate (10 Mbps near living tissues), and non-interference.

Frequency Bands for Medical Purposes

The most used WBAN technologies include Bluetooth, Wibree & ZigBee.



Medical Implant Communication Systems

Wireless Medical Telemetry Services

Industrial, Scientific & Medical

UWB is currently considered the **best candidate** technology for WBANs with:

- good material penetration,
- low power emissions,
- low-interference,
- robustness against multi-path
- accurate sub-cm localizations

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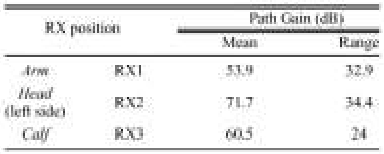
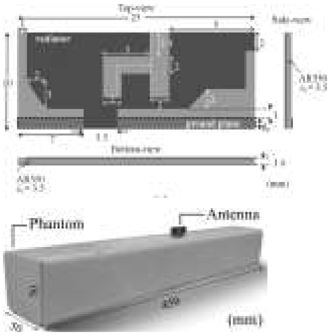
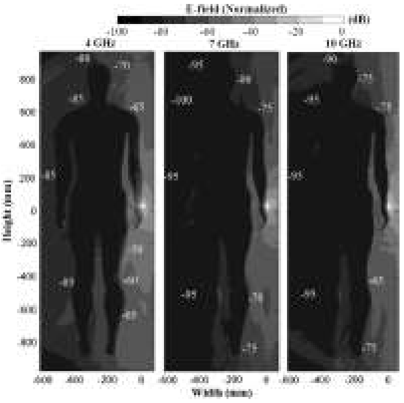
On-Body Comm. @ UWB

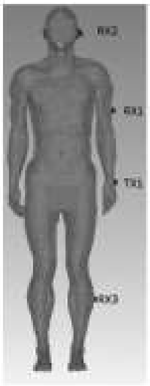
Quarter-wavelength monopole and planar inverted cone antenna **(PICA)** with small ground plane at **UWB** (3–11.2 GHz) for **on-body communications**



RX position		Path Gain (dB)	
		Mean	Range
Arm	RX1	53.9	32.9
Head (left side)	RX2	71.7	34.4
Calf	RX3	60.5	24







Model of a 34 year-old 174 cm-tall adult weighting 70 kg

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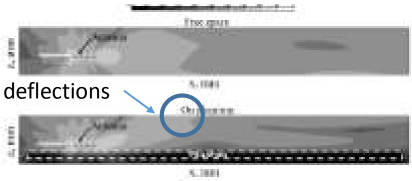
Yagi-Uda for Off-body Communications

Off-body communication, end-fire **Yagi-Uda** at **57-64 GHz band.**

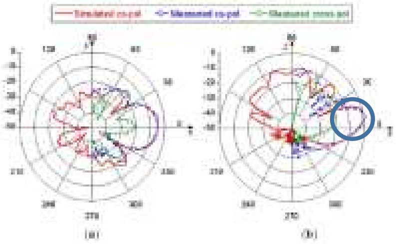
E-field distribution in free space

and **@5.6 mm from human hand phantom**



deflections

E-field distribution in free space and @5.6 mm from human hand phantom. E- and H-planes



Max on-body gain **15.2 dBi**

Back radiation is significantly **reduced** because of the **absorption** in the body.

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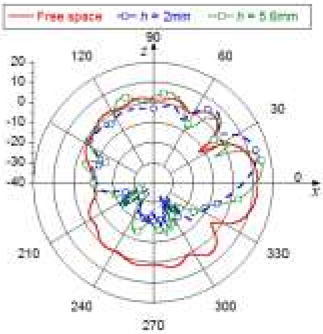
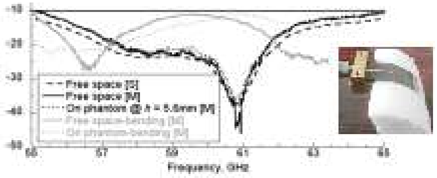
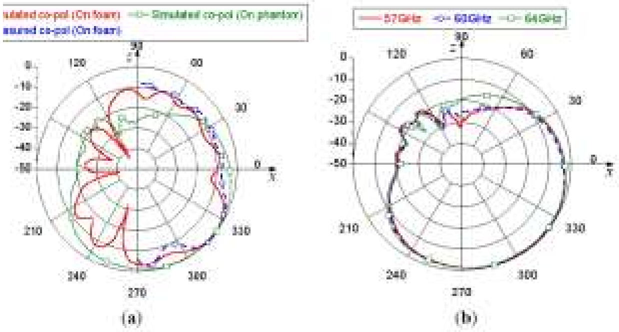
Yagi-Uda for Off-body Communications

Computed gains (H-plane) for different antenna/phantom distances





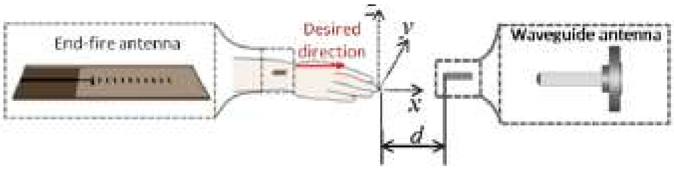
Radiation Patterns (H-plane) of bent antenna on phantom a) @60 GHz and b) @57, 60, 64 GHz



A **significant** effect is noticed on the ***H*-plane** rather than *E*-plane. **Radiation follows the bending**. Same effect is noticed at 57 GHz and 64 GHz.

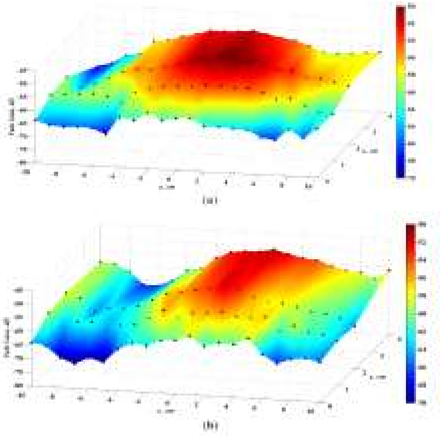
Yagi-Uda for Off-body Communications

Antenna placed on wrist and communicates with an **off-body** transceiver **@5 cm** away



- Maximum path gain for waveguide antenna at z-axis between 3–4 cm respect to the wearable antenna (height corresponding to 10° tilt in *H*-plane)
- Higher path gain noted for waveguide at *y*-axis between −5 cm to 5 cm, corresponding to angular width of ~30°. In fact, the radiation pattern on *E*-plane has angular width (3 dB) of ~30°.

Path gain distribution for:
a) rectangular and
b) real hand phantoms



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Antennas and System for Emerging 5G Communications

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Notes and References are available upon request
Questions are welcome

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