5G for Wearable Applications

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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)

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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* 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)

Requirements for 5G

- ***Data rates***: **peak** data rates of **20 Gbps** and **1 Gbps experienced by the user**. That is, 1000X or 100X the current 4G technology;
- ***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**;
- ***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.

The need for **higher data rates** 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.

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High Data Rate – 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 Rate – 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.
- **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).

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High Data Rate – Increased Bandwidth

- **Propagation Loss**: increasing the transmitting frequency f_c by an order of magnitude, **adds 20 dB** of power loss. 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;

🙂 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 Rate – MIMO

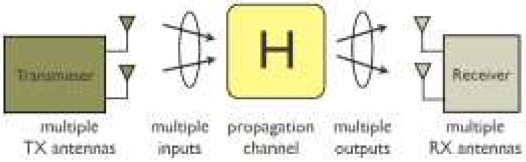
*MIMO systems **embodies the spatial dimension** of the communication that arises once a multiplicity of antennas are available at BS and mobile devices*

They allow **spatial data multiplexing** when the **channel** has the transfer functions between different transmit and receive antenna pairs **largely independent**. In these schemes, **multiple parallel data streams are transmitted simultaneously** and **in the same frequency band** and can be separated at the receiver.

number of paths complex gains

$$\mathbf{H} = \sum_{\ell=1}^{N_p} \alpha_\ell \mathbf{a}_R(\theta_{R,\ell}, \phi_{R,\ell}) \mathbf{a}_T^*(\theta_{T,\ell}, \phi_{T,\ell}).$$

array steering vectors



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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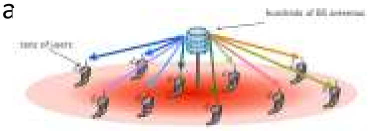
High Data Rate – MIMO

- **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

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

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

- 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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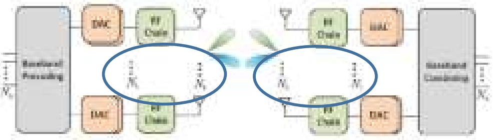
High Data Rate – MIMO

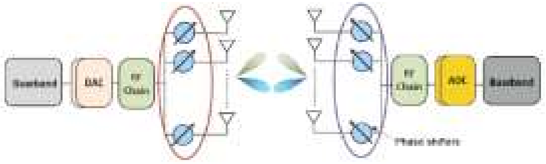


MIMO, at **lower frequencies**, is an exercise in digital signal processing taking place at baseband.

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

MIMO - Analog MIMO



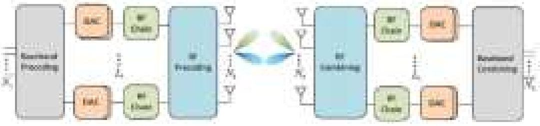
Analog beamforming (supported in IEEE 802.11ad) is one of the **simplest approaches** for applying MIMO in mmWave systems

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

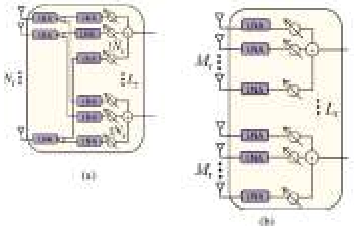
Performance are **limited** by the use of **quantized phase shifts** and the **lack** of **amplitude adjustments**. This makes more challenging to finely tune the beams and steer nulls. **High # of phase shifters** and **high power consumption** are also a concern

> *Several years ago a […] colleague […] told me—while salivating at the number of open research topics in RFID communications—"It's like the 1950s all over again." His point was that, […] in short, a backscattering RFID chip communicates with a reader in the way that digital radios used from at least 40 years ago.*
> Durgin G., *Recent Backscatter Breakthroughs in Higher-Order Modulation,* IEEE RFID Virtual Journal

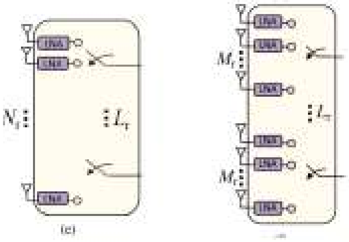
MIMO – Hybrid MIMO



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

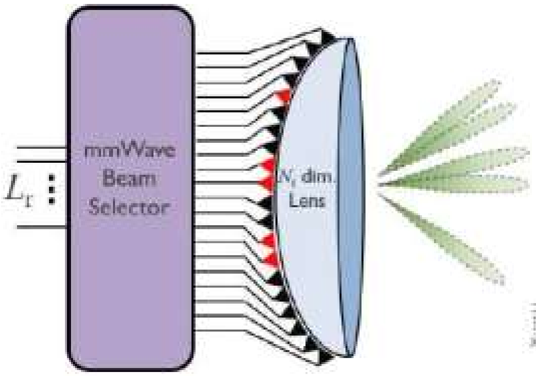


Two hybrid structures are possible: (a) all the antennas can connect to each RF chain, or (b) the array can be divided into subarrays; each subarray connects to its own individual transceiver. Multiple **subarrays reduce hardware complexity** at the expense of **less** overall **array flexibility**



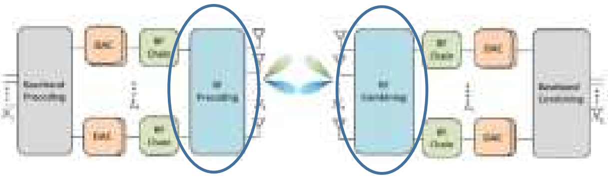
Alternative mmWave hybrid architecture makes use of **switching networks**. It has small losses, **lower complexity and lower power consumption**. Every switch can be connected to all the antennas or to a subset of antennas for larger arrays

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

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Exposure to mmWaves

Besides being seen as traveling electromagnetic waves, mmWave can also be described as having a particle-like nature. In this case, each photon has an energy level given by:

$$E = hf = \frac{hc}{\lambda}$$

mmWaves **energy *E*** ranges **from 0.1 to 1.2 meV** ; this energy **is not enough to remove electrons from an atom or a molecule** (typically 12 eV are required), phenomenon linked to cancer.

Dosimetric quantities to measure RF Exposure :

$$SAR = \frac{P_{diss}}{m} = \frac{\sigma|E|^2}{\rho} \left[\frac{W}{kg}\right]$$

quantitative measure of RF power absorbed in a living body

$$PD = \frac{|E_i|^2}{\eta} = \eta|H_i^2| \; [\frac{W}{m^2}]$$

In **near-field**, free space impedance ***η*** **is function of position**.

Transient temperature

Used to evaluate the medium- and high-power effects of radiation.

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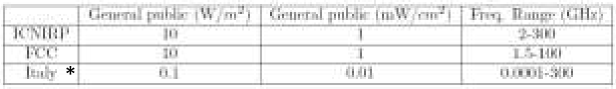
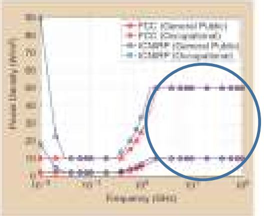
Exposure to mmWaves

For mmWaves, ICNIRP and FCC **use PD** as a basic restriction in the mmWave **exposure guidelines**: 10 W/m^2 for the **general public** and 50 W/m^2 for the **occupational groups**.



	General public (W/m^2)	General public (mW/cm^2)	Freq. Range (GHz)
ICNIRP	10	1	2-300
FCC	10	1	1.5-100
Italy *	0.1	0.01	0.0001-300

Far-field



Near-field

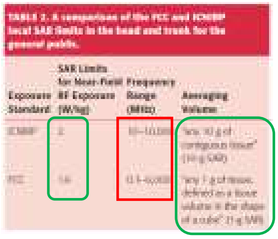


TABLE 2. A comparison of the FCC and ICNIRP local SAR limits in the head and trunk for the general public.

Exposure Standard	SAR Limits for Near-Field RF Exposure (W/kg)	Frequency Range (MHz)	Averaging Volume
ICNIRP	2	10–10,000	"any 10 g of contiguous tissue" (10-g SAR)
FCC	1.6	0.1–6,000	"any 1 g of tissue, defined as a tissue volume in the shape of a cube" (1-g SAR)

🟥 **No SAR exposure** values are **provided for mmWaves**

***No dosimetric** quantities are given for **near-field mmWave** exposure.*

🟩 Maximal localized SAR in head and trunk: **FCC**, 20x the whole-body averaged SAR (1.6 W/kg); **ICNIRP** (2 W/kg). European and American regulations **differ** for both the **SAR values** and the **definition of tissue mass** used to define the SAR.

*The **1-g SAR** is a **more meaningful measure** of localized RF radiation absorption inside the head (where a whole eye has a total mass of about 10g) and the trunk.*

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*Guidelines in Italy make it difficult to locate typical base station antennas on apartment buildings and other low structures near people.

Current Compliance Evaluation Process

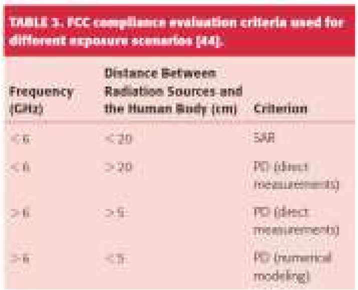

TABLE 3. FCC compliance evaluation criteria used for different exposure scenarios [44].

Frequency (GHz)	Distance Between Radiation Sources and the Human Body (cm)	Criterion
<6	<20	SAR
<6	>20	PD (direct measurements)
>6	>5	PD (direct measurements)
>6	<5	PD (numerical modeling)

The FCC guidelines:

- <6 GHz
    - distances <20 cm, SAR should be evaluated
    - distances >20 cm (base stations), PD should be evaluated

- >6 GHz (mmWave)
    - distances <5 cm, PD evaluations computed numerically

In near-field, computation is more complex because it depends on position, antenna geometry, orientation etc

*Current exposure guidelines are **not appropriate** for mmWave devices*

Current Compliance Evaluation Process - Example

Consider a 10 mm, **60 GHz** phased array (**far-field at 4 cm**) with antenna gain of 10 dBi transmitting 100 mW

● **@10 cm** (far-field) from the body

PD is **0.8 mW/**cm^2, **below** the FCC allowed value of 1 mW/cm^2

	Gen. pub.(mW/cm^2)	Freq. Range (GHz)
FCC	1	1.5-100

Compliant

🟨 **@<4 cm** (near-field) from the body

Numerical simulations are needed. These methods are well established at lower frequencies, but are not yet at mmWave frequencies.

TABLE 1. A comparison of the FCC and ICNIRP local SAR limits in the head and trunk for the general public.

Exposure Standard	SAR Limits for Near-Field RF Exposure (W/kg)	Frequency Range (MHz)	Averaging Volume
FCC	1.6	0.1–6,000	Any 1 g of tissue, defined as a tissue volume in the shape of a cube (1-g SAR)

peak local (unaveraged) **SAR** level **> 22 W/kg**

Not *compliant*

*Current SAR limits are **not appropriate** to be used at mmW frequencies*

*Simulation and measurements of **temperature** and **temperature increase** in the near-field of mmWave should be **more valuable** than estimates of PD*

TABLE 2. FCC compliance evaluation criteria used for different exposure scenarios [44].

	Frequency (GHz)	Distance Between Radiation Sources and the Human Body (cm)	Criterion
●	>6	>5	PD (direct measurements)
🟨	>6	<5	PD (numerical modeling)

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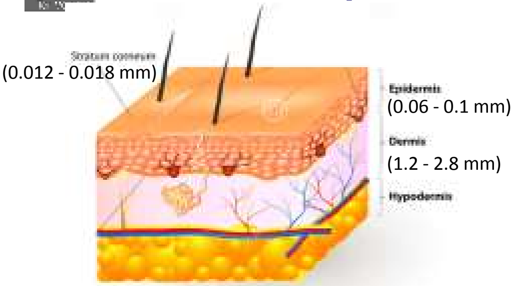
Skin Properties and Heating



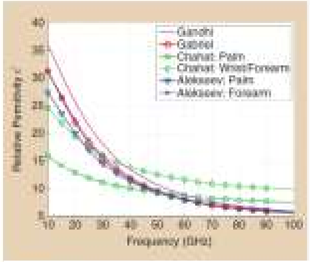
Stratum corneum: **low water content** (15-40%)
Total water concentration in the **rest** of the epidermis and dermis is **70-80%**.

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

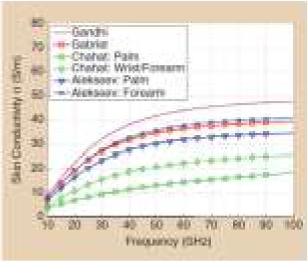
- penetrates the stratum corneum;
- is rapidly absorbed within the epidermis and dermis;
- does not propagate further into the body.

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.*

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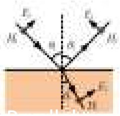
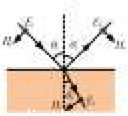
Skin Properties and Heating



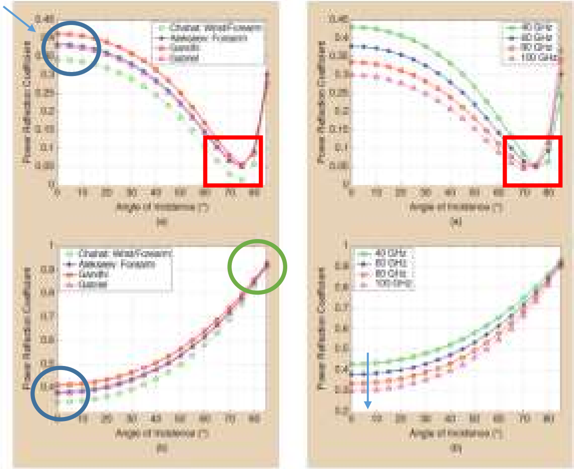
Parallel pol.



Perpendicular pol.

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

Parallel *vs* perpendicular polarizations



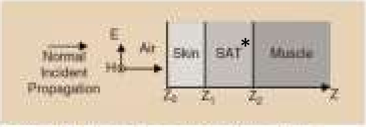
Brewster angles of 60º to 80º at various frequencies

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.*

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

Skin penetration



A 1-D three-layer human tissue

* subcutaneous adipose tissue

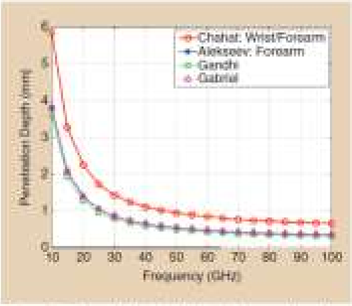


Figure 6. The penetration depth in the human skin with the increase of exposure frequency.

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

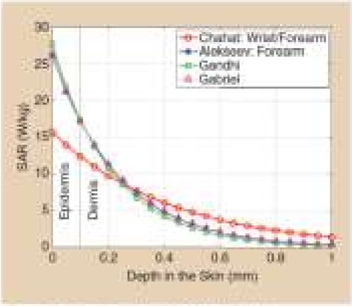
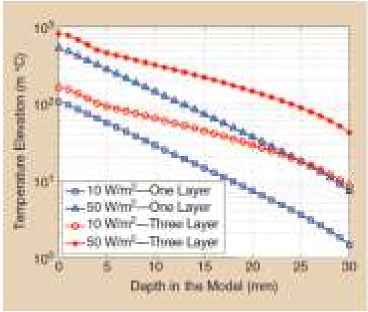


Figure 7. The attenuation of SAR in the skin for an incident PD of 10 W/m² at 60 GHz.

> 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**
- **Eyes are vulnerable** to mmWave radiation-induced heating as they **lack** sufficient **blood flow** to redistribute the generated heat;
- mmWaves could **activate natural kill (NK) cells** that remove tumor cells;
- **membranes might be affected** by mmWaves at PD levels typically expected from wireless communication systems (0.9 mW/cm^2)
- mmWaves might **accelerate healing** of wounds and heal wounded skin without leaving scars*
- mmWave are **not genotoxic** (i.e.: they do not induce cancer)
- **Long-term effects** of heating due to mmWave frequencies are **unknown**

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

Summary

Exposure

- ***No dosimetric*** *quantities are given for* ***near-field mmWave*** *exposure*
- *Current exposure guidelines are* ***not appropriate*** *for mmWave devices*
- *Simulation and measurements of* ***temperature*** *and* ***temperature increase*** *in the near-field of mmWave should be* ***more valuable*** *than estimates of PD*

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*
- ○ *The* ***1-g SAR*** *is a* ***more meaningful measure*** *of localized RF radiation absorption inside the head (where a whole eye has a total mass of about 10g) and the trunk*

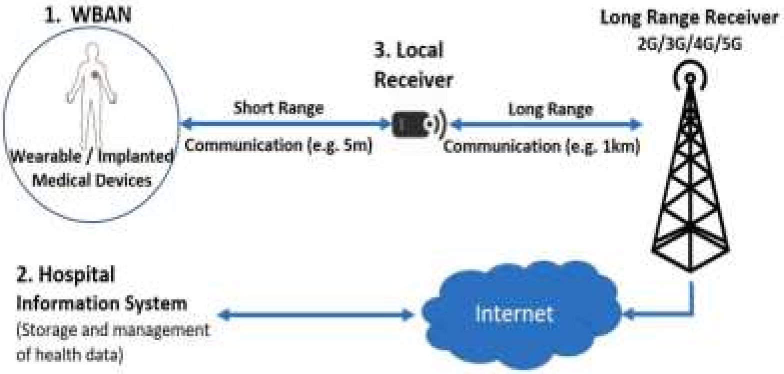
Practical

- ❑ *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

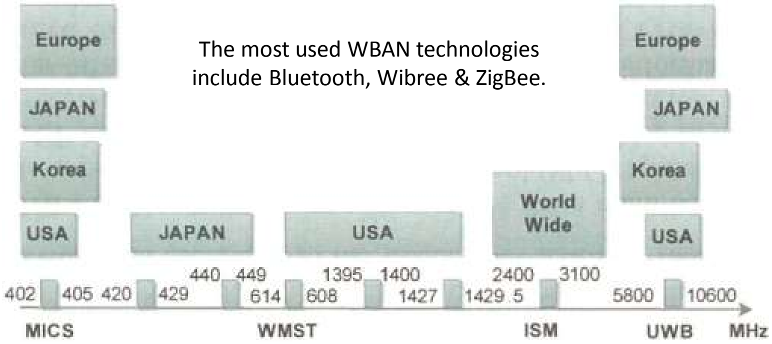
- **Reaction times** of 100 ms, 10 ms, and 1 ms required for auditory, visual, and manual interaction, respectively, so that **all human senses can interact with machines**, hear and see things remotely
- **Service robots** for care will join the labor force with logistic, cleaning, and monitoring roles. Robots will also need interpret human emotions, interact with people, and assist patients and old people in hospitals

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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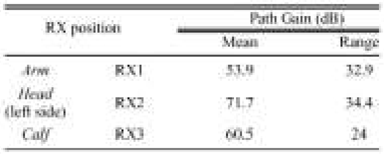
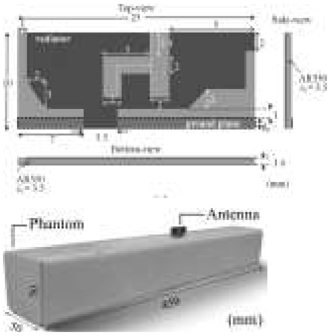
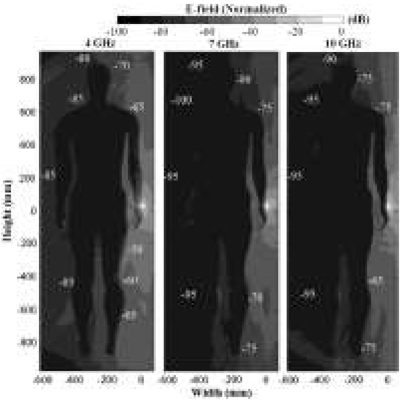
On-Body Comm. @ UWB

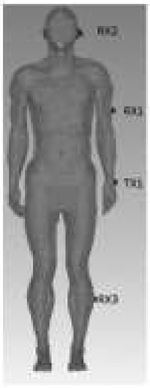


RX position		Path Gain (dB)	
		Mean	Range
Arm	RX1	53.9	32.9
Head (left side)	RX2	71.7	34.4
Calf	RX3	60.5	24

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







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

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Slot Antenna Array

mmWave beam forming network (Butler Matrix) + planar 4x4 array: **28 GHz**, 1 GHz BW; Max gain: 12 dB, min: 8 dB

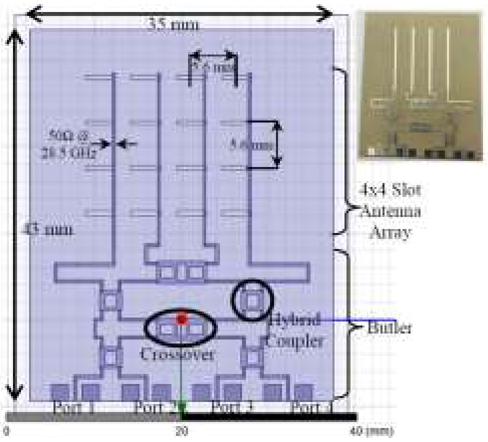

Fig. 1 Complete Switched Beam mm-wave Antenna Array. Figure inset shows the Top layer of the fabricated Antenna Array

The beams radiated from the antenna array were steered to four different locations; ±20° and ±45°.

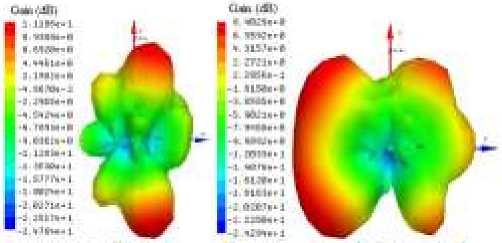

Fig. 4 Radiation Pattern when port (a) 1 (b) 2 is excited

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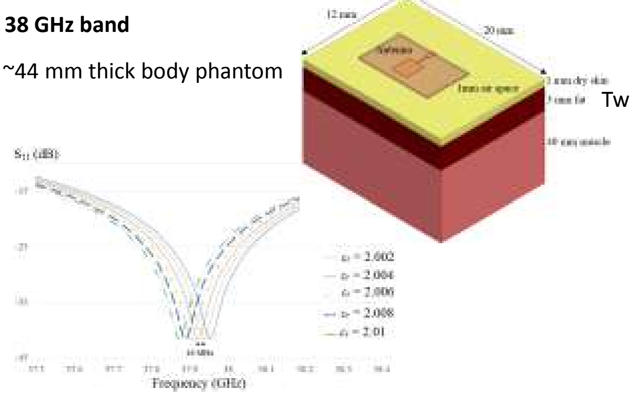
Other Antennas

Fabric-based rectangular patch antenna and uStrip feed line with body temperature sensing

38 GHz band

~44 mm thick body phantom



Proportional **decrease** of resonant frequency with **increasing dielectric constant**

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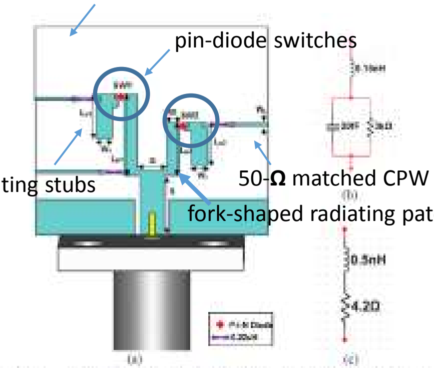
20.7 - 36 GHz



liquid crystal polymer substrate

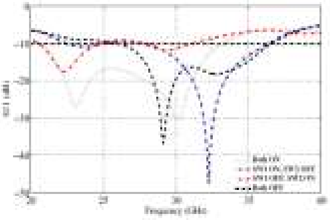
pin-diode switches

Two radiating stubs

50-**Ω** matched CPW lines.

fork-shaped radiating patch

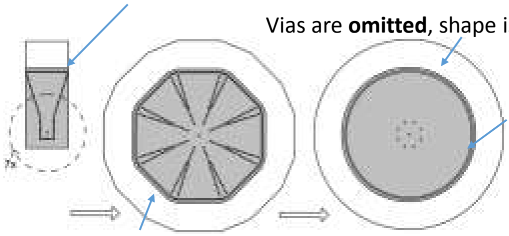
Fig. 1 Simulated layout: (a) Proposed flexible frequency reconfigurable antenna; (b) Diode OFF state circuit model; (c) Diode ON state model.



suggested fabrication with low-cost **inkjet printing**

Disc-like Antenna for On-Body Comm.

Substrate Integrated Waveguide (SIW) horn antenna at **61 GHz** (59.3 to 63.4 GHz)

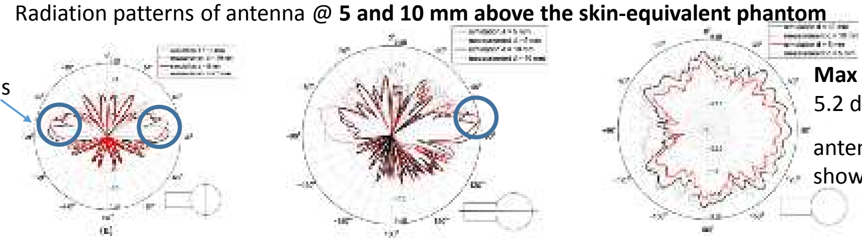


Vias are **omitted**, shape is changed to be perfectly circular

transition rings (3) improve radiation performance and impedance matching

Rotating the SIW horn, a set of horn antennas fed by a feeding pin reach an **omnidirectional** radiation pattern.

Radiation patterns of antenna @ **5 and 10 mm above the skin-equivalent phantom**



deflections

Max gain in h-plane: 5.2 dBi (d = 10 mm).

antenna on phantom shows **higher max gain**

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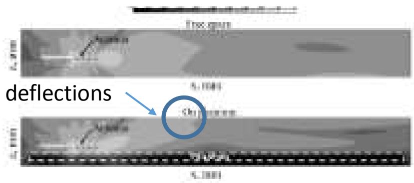
Yagi-Uda for Off-body Communications

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

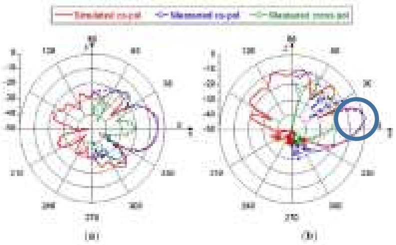

(a) (b)

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

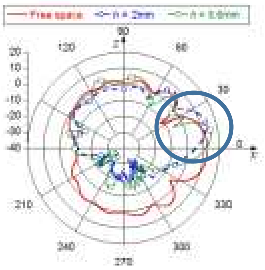


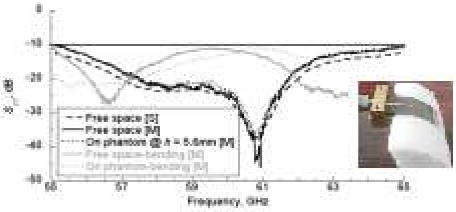
Max on-body gain **15.2 dBi**

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

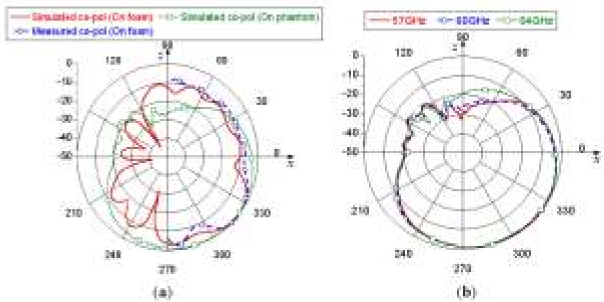
Yagi-Uda for Off-body Communications

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





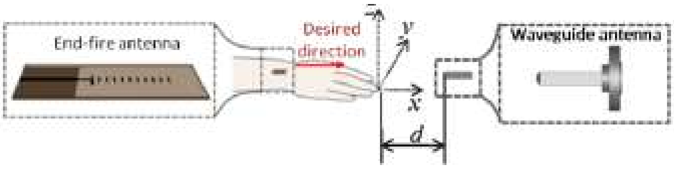
Radiation Patterns (H-plane) of bent antenna on phantom a) @60 GHz and b) @57, 60, 64 GHz



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.

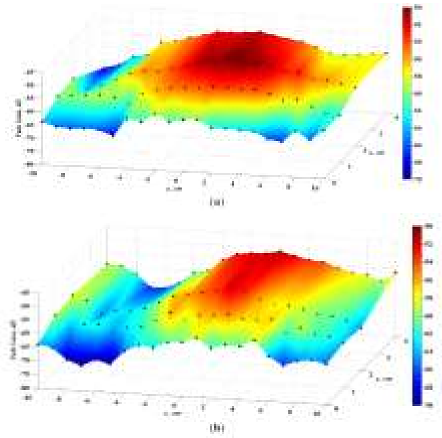
Yagi-Uda for Off-body Communications

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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On-Body Antennas on Textile

Microstrip-fed End-fire Yagi-Uda. Max on-body **gain 11.9 dBi @57-64 GHz**. **Reduced efficiency**


(a)

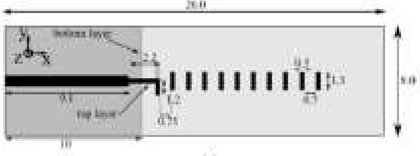

(b)

1 driven dipole + 10 directors

On 0.2 mm-thick cotton fabric

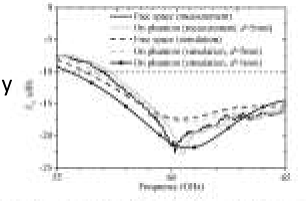
S_{11} **not affected** by antenna/body separation @5 mm and 1 mm.

Microstrip truncated ground plane at 1 mm from driving dipole acts as a reflector

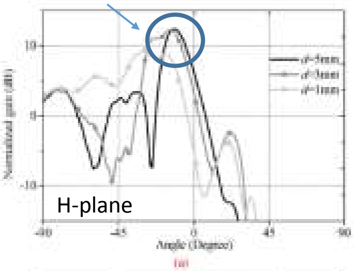


(c)

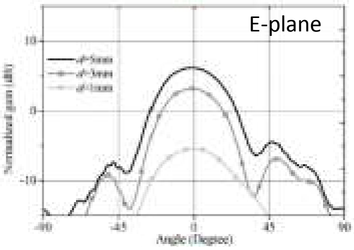
Driving dipole and Balun between the *microstrip feed* and dipole are built on the top and bottom sides of the textile substrate.



15° tilt on phantom



H-plane



E-plane

Computed radiation pattern **decreases** with d. **@0 mm**, it is short-circuited. This can be avoided by embedding the antenna between two fabrics.

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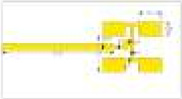
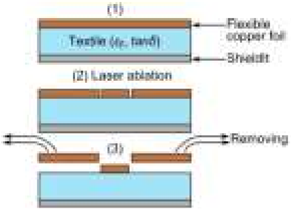
Off-body Comm.

57-64 GHz band 2x2 patch antenna array on commercial textile.





Fabrication process uses thin and flexible 0.07 mm **thick copper foil**; **ShieldIt Super** as ground plane. Copper foil is etched with a **laser machine**.

The relative permittivity of the substrate was retrieved using open-stub technique.

Human body effects on the antenna characteristics are very **weak** thanks to the **ground plane**.

P_T = 10 dBm, EIRP = 19 dBm, G_{RX} = 15 dBi, Rx Sensitivity: -50 dBm
Max on-body gain: 8 dBi
Max distances: 5.4 m (LoS); 1.6 m (NLoS)

Non-textile *antennas should be* ***employed*** *when possible since they have* ***higher efficiency***

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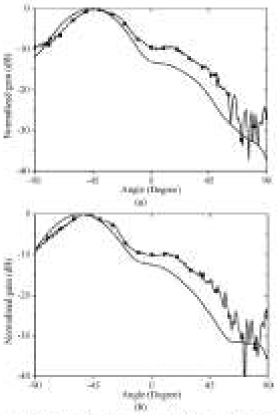
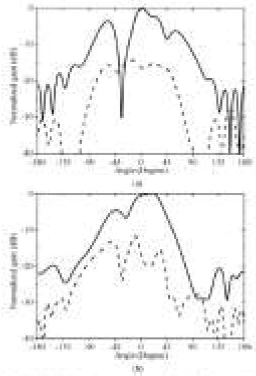
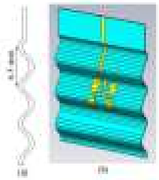
Bending and Crumpling



Measured and simulated H-plane in two bending configurations



Simulated effects of crumpling on a) E- and b) H-planes



*In both cases, the s_{11} **remains** well **matched** in the band of interest*

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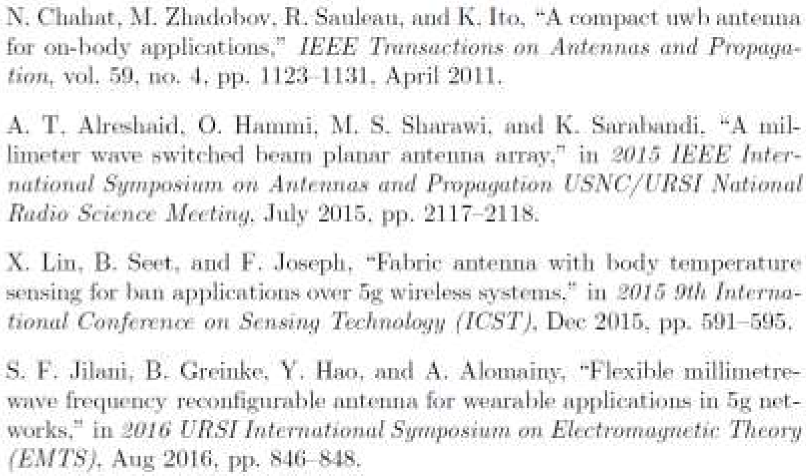
References on Wearable Antennas



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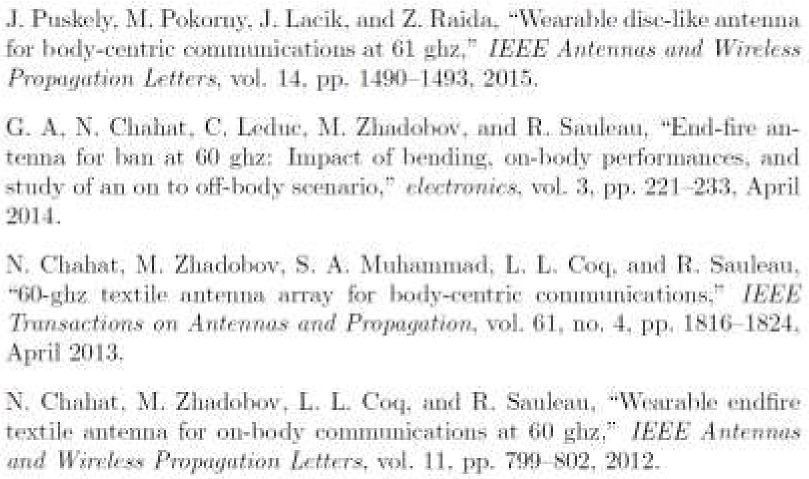
References on Wearable Antennas



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N. Chahat, M. Zhadobov, S. A. Muhammad, L. L. Coq, and R. Sauleau, “60-ghz textile antenna array for body-centric communications,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 1816–1824, April 2013.

N. Chahat, M. Zhadobov, L. L. Coq, and R. Sauleau, “Wearable endfire textile antenna for on-body communications at 60 ghz,” *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 799–802, 2012.

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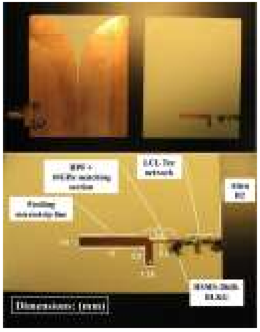
mmWave RFIDs

A **10 GHz** “*mmWave*” RFID systems is achieved by adding an external mixing element between the tag antenna and a standard RFID chip. **The RFID UHF chip operates as usual**

Final Tag



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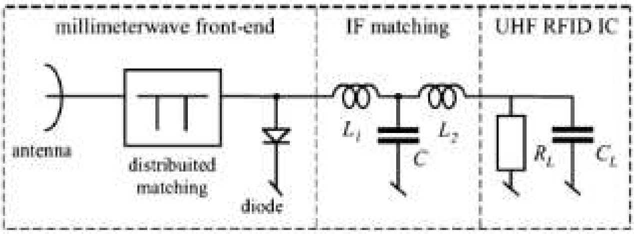
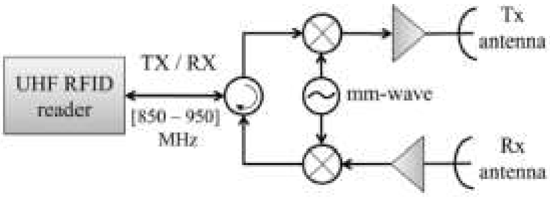
mmWave RFID tag



mmWave RFID reader



The reader’s ports are equipped with **external mixers** to convert the reader output to millimeter waves and received millimeter-wave signal to RFID carrier frequency

mmWave RFIDs

For **precise ranging** in dense indoor RFID applications, a **large** absolute **BW is required**

Since the BW of UHF systems is restricted, **34.3-34.8 GHz** mmWave RFID tags in **short range (1-10 m)** applications are proposed

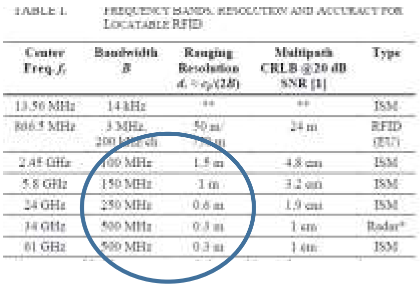
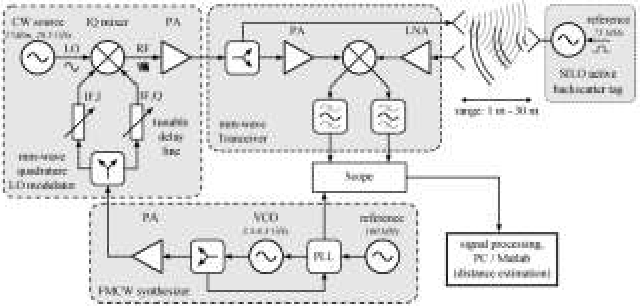


TABLE I. FREQUENCY BANDS, RESOLUTION AND ACCURACY FOR LOCATABLE RFID

Center Freq. f_c	Bandwidth B	Ranging Resolution $d_r \approx c_0/(2B)$	Multipath CRLB @20 dB SNR [1]	Type
13.56 MHz	14 kHz	**	**	ISM
866.5 MHz	3 MHz, 200 kHz ch	50 m/ 750 m	24 m	RFID (EU)
2.45 GHz	100 MHz	1.5 m	4.8 cm	ISM
5.8 GHz	150 MHz	1 m	3.2 cm	ISM
24 GHz	250 MHz	0.6 m	1.9 cm	ISM
34 GHz	500 MHz	0.3 m	1 cm	Radar*
61 GHz	500 MHz	0.3 m	1 cm	ISM



frequency modulated continuous wave (FMCW) RFID ranging approach

- ranges: 0.7 to 11.5 m
- measurement error: 7 cm
- measurement precision: <3 mm

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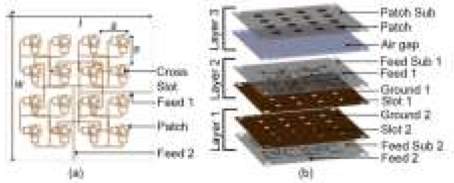
mmWave chipless RFIDs

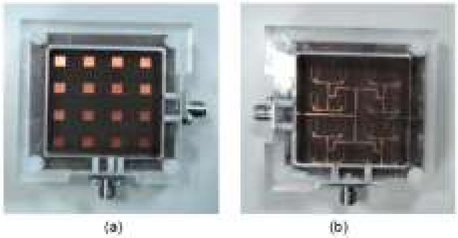
4 × 4 dual polarized aperture-coupled microstrip patch antenna **(ACMPA)** array

22–26.5-GHz band; **16-dBi** realized gain



(a) (b)

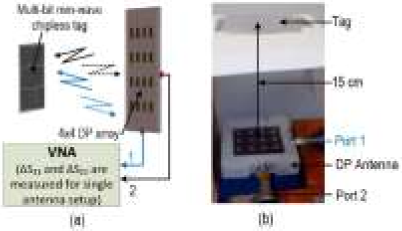
Fig. 7. (a) Plan and (b) 3-D view of the 4 × 4 mm-wave DP ACMPA array.



(a) (b)

Fig. 10. (a) Top and (b) bottom view of the assembled 4 × 4 DP ACMPA array.

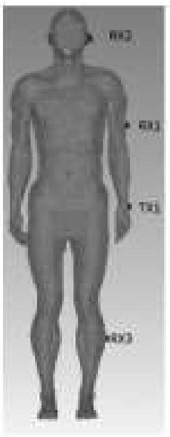
reading performance verified **@15 cm** on 10 thermal printed mm-wave tags on the paper substrate

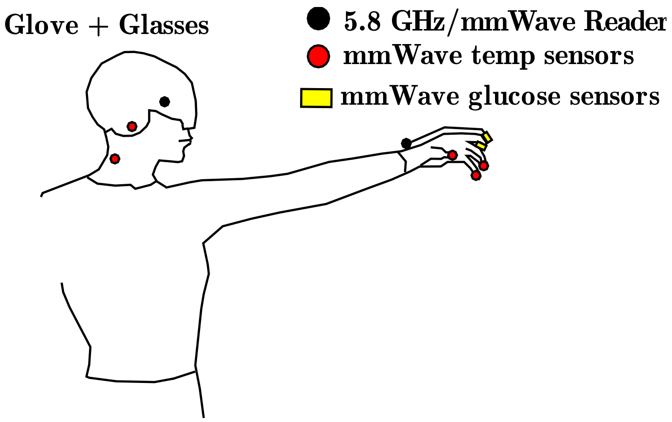


(a) (b)

Fig. 13. (a) Block diagram and (b) laboratory setup of the mm-wave tag measurement using the 4 × 4 mm-wave DP ACMPA array.

Health Monitoring & Augmented Sensing





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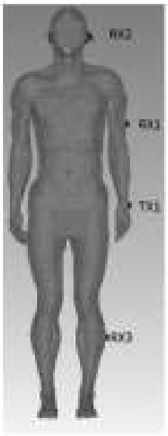
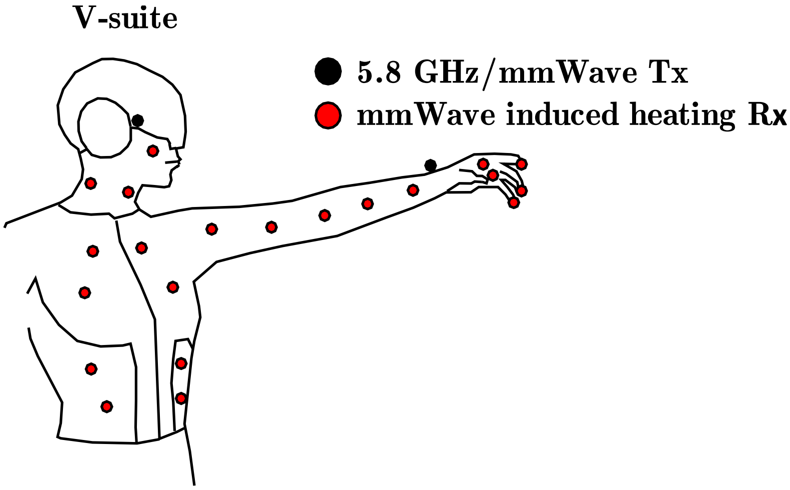
Localized Heating Sensations





5G for Wearable Applications

Francesco Amato

20 Dec. 2018

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Paper 1/2 – Conference

- Extrapolated and measured electromagnetic models at 60 GHz are available (see Rappaport)
- Identify body parts (Arm, Breast, Neck) and body types (Man & Woman)
- Simulate 50 Ohm antennas at 60 GHz -> get s_{11}'s and gains
- Paper Results: one or more tables (+ s_{11} and gain plots)

Antenna 1

	Man	**Woman**
Arm	(gain, s11)$_{AM}$	(gain, s11)$_{AW}$
Breast	(gain, s11)$_{BM}$	(gain, s11)$_{BW}$
Neck	(gain, s11)$_{NM}$	(gain, s11)$_{NW}$

Antenna 2

	Man	**Woman**
Arm	(gain, s11)$_{AM}$	(gain, s11)$_{AW}$
Breast	(gain, s11)$_{BM}$	(gain, s11)$_{BW}$
Neck	(gain, s11)$_{NM}$	(gain, s11)$_{NW}$

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Paper 2/2- Journal

- Build 60 GHz skin phantom (see Za..)
- Measure s_{11} and off-body gains/s_{21} (?)
- Compare measurements *vs* simulations

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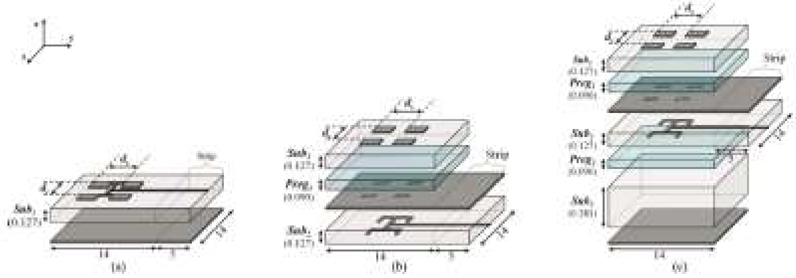
Fabrication and feeding



1. Schematic of antenna array structures. (a) A_1. (b) A_2. (c) A_3. Dimensions are in mm.