Millimeter waves: propagation issues

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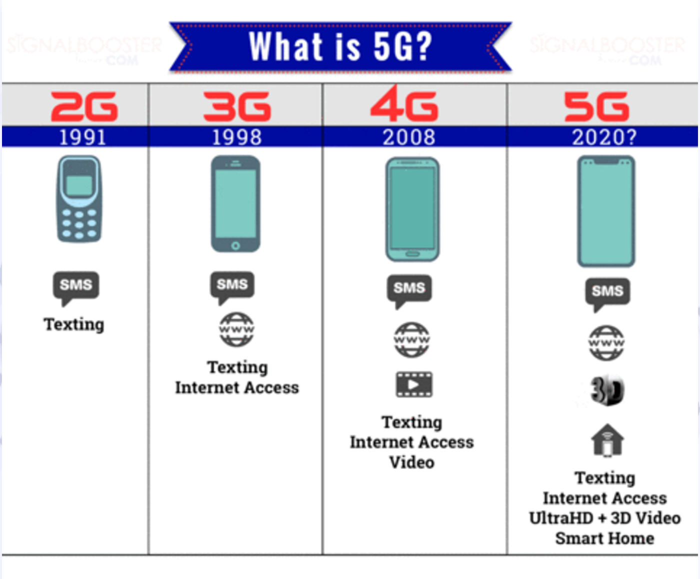
Outline

What is 5g?


What is 5G?
SIGNALBOOSTER.COM
2G
1991
SMS
Texting
3G
1998
SMS
WWW
Texting
Internet Access
4G
2008
SMS
WWW
Texting
Internet Access
Video
5G
2020?
SMS
WWW
3D
Texting
Internet Access
UltraHD + 3D Video
Smart Home

Old generations

	1G	2G	3G	4G	5G
Year	1984	1991	1998	2008	2020?
Throughput	2 kbps	64 kbps	2 Mbps	1 Gbps	20 Gbps
Standards	AMPS, TACS, etc	GSM, GPRS, EDGE, etc	UMTS, HSPA, etc	LTE	NR
Frequencies	150 MHz / 450 MHz / 900 MHz	900 MHz / 1800 MHz	850 MHz/ 900 MHz/ 1800 MHz / 2100 MHz	800 MHz/ 1800 MHz / 2100 MHz / 2400 MHz	Sub 1 GHz 1 GHz ≤ f ≤ 6 GHz f> 6 GHz
Bandwidth	30 KHz	25 MHz	100 MHz	100 MHz	≅ 1 GHz
Characteristics	Voice /Low quality, security, battery usage	SMS / weaker signal, worst coverage	Web Browsing, Video Streaming / Insufficient Bandwidth	Security, low cost per bit / battery usage, complex implementation	Better coverage, better battery usage / Difficult management of security problems
					

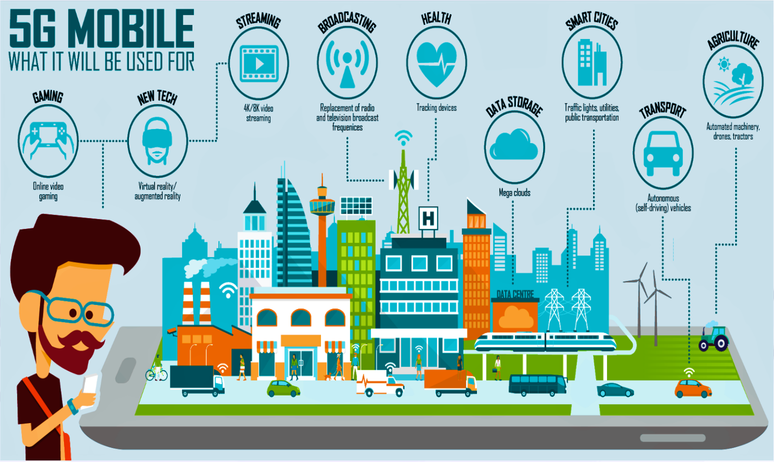
5g vs old-generations

Previous generations of mobile networks addressed consumers predominantly for voice and SMS in 2G, web browsing in 3G, and higher-speed data and video streaming in 4G.

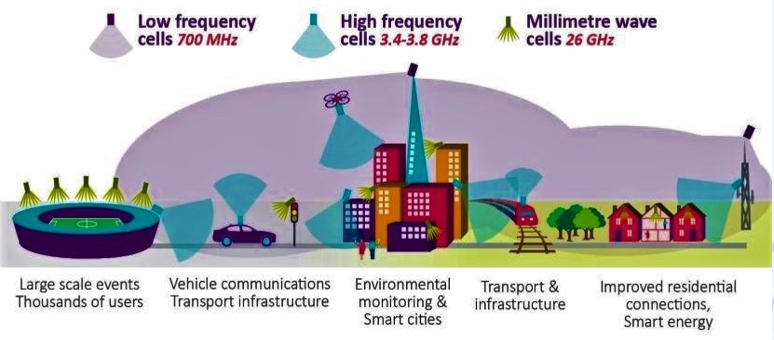
The transition from 4G to 5G will serve both consumers and multiple industries.

- higher data rates and spectrum utilization;
- 4K/8K video streaming;
- virtual and augmented reality;
- ...

A heterogeneous network



A heterogeneous network



A heterogeneous network

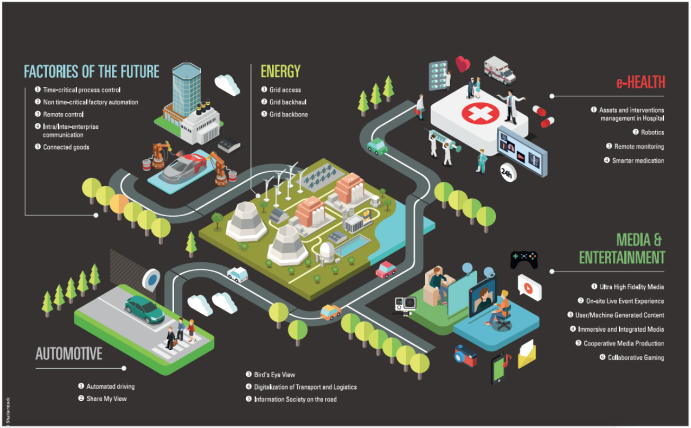
To support a broad set of use cases, the new standard identified three primary requirements:

- Massive M2M communications for IoT applications.
- Ultra-low latency enabling life-saving car-to-car connectivity.
- Gigabit speeds

No single wireless technology will be able to meet these characteristics, so 5G will be defined by a heterogeneous network that integrates 5G, 4G, Wi-Fi, and other wireless technologies.

5G as a driver for industrial and societal changes

Europe is faced with economic and societal challenges such as ageing of populations, societal cohesion, sustainable development. The introduction of digital technologies in economic and societal processes is key to address these challenges. 5G network infrastructures will be a key asset to support this societal transformation, leading to the fourth industrial revolution impacting multiple sectors.



Use cases

5G top use cases include massive machine communications.

Use cases

A new mobile wireless scenario, completely different from the human-centric one that characterized legacy communication standards, is expected.

- A tremendous amount of data traffic is expected to originate from machine-type communication services leading to massive machine communications (MMC).
- Direct device-to-device (D2D) communication is a key communication scenario (i.e.; for cellular traffic offloading, coverage extension, emergency communication, etc.).
- Latency-critical applications (e.g.; remote driving, industry automation, tele-protection, and mission-critical controls).
- Vehicle-to-vehicle (V2V).

Smart cities

Smart home

Internet of medical things

Gaming and virtual reality

Technological challenges

Cyber security

Cyber security

It is a real challenge

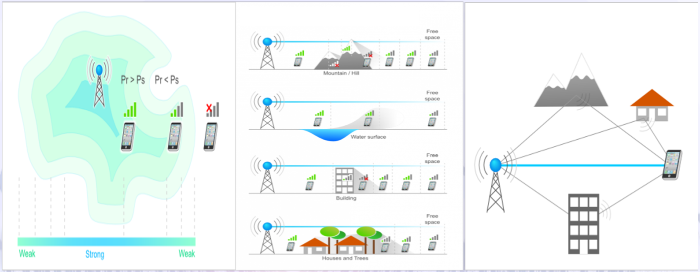
As we pursue the connected future, however, we must place equivalent-if not greater-focus on the security of those connections, devices, and applications

Software is the core of the whole architecture

- Centralized, hardware-based switching is replaced by distributed, software-defined digital routing.
- Higher-level network functions formerly performed by physical appliances are now software-based.
- The Dynamic Spectrum Sharing is managed by software.
- Early generation of artificial intelligence.

Propagation channel

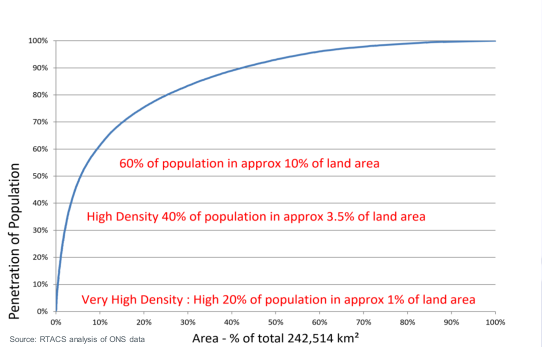
Source → Transmitter → **Channel** → Receiver → Destination



$$Throughput\left(\frac{bit}{s}\right) = B(Hz) \times Spectral \quad Efficiency\left(\frac{bit}{s \times Hz}\right) \tag{1}$$

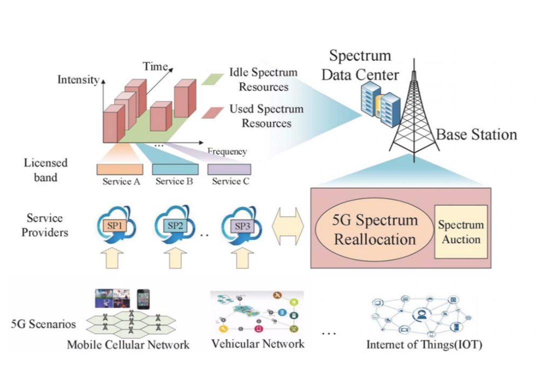
Outline

Is the spectrum a “scarce” resource?



The provision of 60% population coverage would need only 10% land area coverage. the more sparsely populated areas will often have the most unused spectrum.

Dynamic Spectrum Allocation



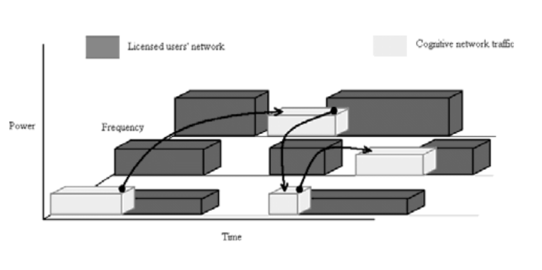
By sensing the absence of primary users, secondary users can use the shared spectrum when services of users in the primary networks are guaranteed

Dynamic Spectrum Allocation

How it works

- The BS provides a number of services (voice, video, vehicle network communication, etc.) using licensed bands.
- In each time slot the request of services comes randomly.
- It may happen that some services saturate the available bands while other bands are underused with limited requests.
- The BS may flexibly allocate the spectrum by “renting” temporarily the unused spectrum among the requesting services.

Dynamic Spectrum Allocation

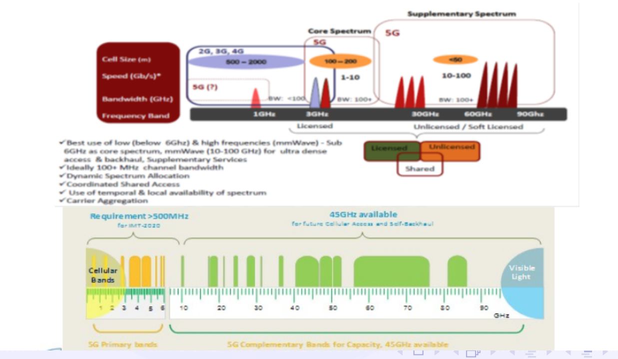


A cognitive radio network can utilize these spectrum holes for its data transmission with minimized interference to and from the primary users. These spectrum holes are generally utilized using Carrier Sense Multiple Access (CSMA) technique

Outline

Frequency bands

To achieve higher data rates, radio frequencies above 6 GHz have been attracting attention as one of the promising solutions because of their potential to allow wider bandwidths than legacy radio systems operating below 6 GHz.



Frequency bands

Three frequency ranges are receiving attention to meet requirements of different propagation scenarios

Sub-1 GHz

- Ideal coverage band could provide a very useful means of extending a superior 5G user experience into rural areas and deep inside buildings.
- Could not support extremely wide bandwidths and therefore enable the fastest possible data rates
- But Help prevent a new digital divide by ensuring the improved experience.
- Reaches more people in both developed, and especially developing, markets.

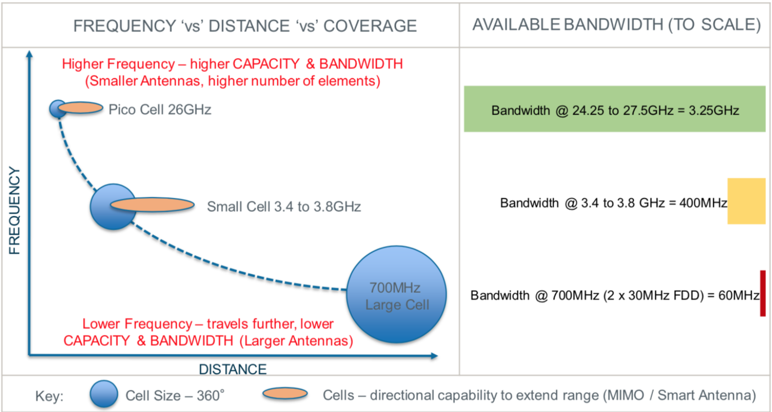
1-6 GHz

- There are numerous existing mobile bands between 1 GHz-2.6 GHz, and when 5G technology is ready to deploy there may be others between 2.6 GHz and 4 GHz.
- Although these bands offer a reasonable mixture of coverage and capacity they are unlikely to be able to support the highest potential 5G data rates without carrier aggregation.

Above 6 GHz

- This spectrum could support very wide channel sizes and therefore extremely fast data rates, and massive additional mobile network capacity, making it fertile territory for 5G research.
- However, heavy reliance on these bands without complimentary lower frequency spectrum may mean 5G services are limited to small urban areas and inside buildings as its radio propagation qualities would favor small cell sizes.

Frequency vs distance vs coverage



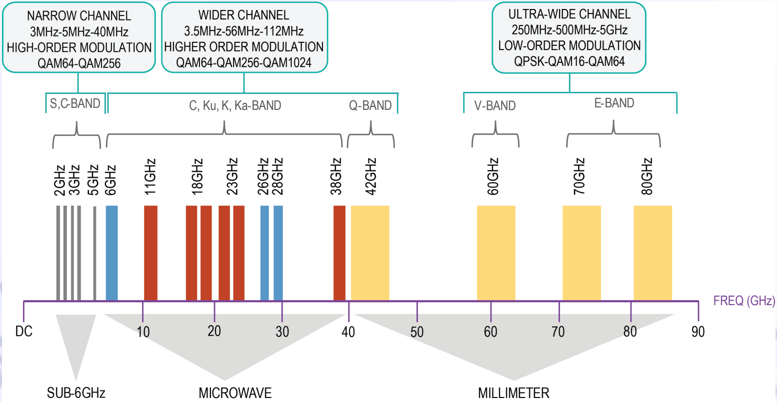
Propagation issues

The entire radio spectrum up to 5.8 GHz that has been used for global wireless communications throughout the past 100 years easily fits within the bandwidth of the single 60 GHz unlicensed band.

mmWave technology

The technology started so see its early applications in Radio Astronomy in the 1960's, followed by applications in the military in the 70's. In the 80's, the development of millimeter-wave integrated circuits created opportunities for mass manufacturing of millimeter wave products for commercial applications.

Millimeter-wave: What they are ?

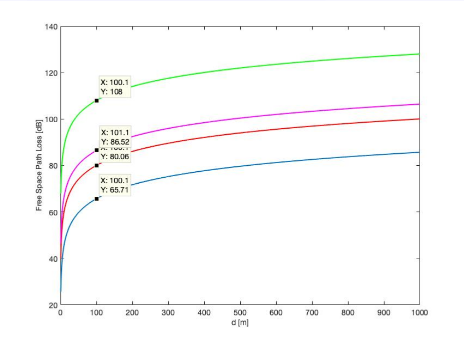


- V-Band: License Free, 60 GHz Band with over 5 GHz of available spectrum.
- E-Band: Lightly Licensed, 70/80 GHz Band with over 10 GHz of available spectrum.

Outline

Path Loss

The free space path loss



Path loss increases dramatically by moving up to mmWave frequencies.

Beyond Friis' free space loss

- This behavior is due to the Friis formula that predicts a path loss that depends on λ^{-2}:

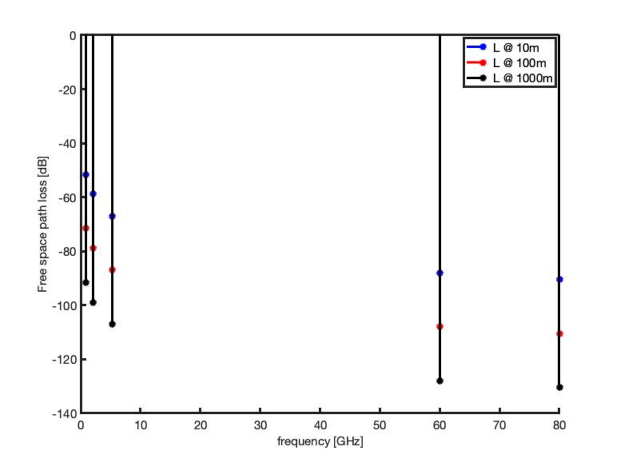
$$L = \left(\frac{4\pi r}{\lambda}\right)^2 \quad (2)$$

Free space PL

According to (2), @ 10m L is:

- -45.7dB @ 460MHz;
- -60dB @ 2.4GHz;
- -66.4dB @ 5GHz;
- -88dB @ 60GHz;

Path Loss



The PL @ mmW frequencies increases dramatically with respect to legacy frequencies

Beyond Friis' free space loss

Are mmWave frequencies a convenient choice?

These numbers show that moving up to mmWave is non trivial if omnidirectional antennas are used.

- A close up at the formula (2) clearly points out that this behavior is due to the Friis free space path loss law that is based on the EIRP:

$$P_r = \frac{EIRP}{4\pi d^2} A_{eff} = \frac{P_t G_t G_r}{Losses} \left(\frac{4\pi d}{\lambda} \right)^2 \quad (3)$$

- where $A_{eff} = A_{max} e_{max}$ is the effective area of the antenna

Beyond Friis' free space loss

Friis formula tells only part of the story

In fact, there is a hidden benefit to propagation at mmWave frequencies that is not at all obvious at a first look at Friis equation.

Arrays of radiating elements

The benefit relies on the fact that @ mmWave is is easy to design very directional antennas calling for effective physical form factor whose gain is substantially higher than the UHF one. This large gain partially compensates the large path loss.

Antenna gain

- The gain of any antenna can be expressed as a function of its effective area and the frequency:

$$G_{max} = e_{max} A_{max} \left(\frac{4\pi}{\lambda^2} \right) \tag{4}$$

- where e_{max} is the maximum efficiency of the antenna, A_{max} is the maximum effective aperture and G_{max} is the maximum gain (in the boresight direction).

Antenna gain

It is clear that:

- G_{max} increases for either increasing frequency or increasing effective aperture.
- G_{max} increases, for a fixed physical antenna aperture, with increasing frequency.

Antenna gain

- Consider an adaptive antenna array that consists of identical antenna elements whose max length is D.
- According to (4), G_{max} of each radiating element is (under matching conditions):

$$G_{max} \propto \left(\frac{4\pi}{\lambda^2}\right) e_{max} D^2 \tag{5}$$

- For a N-element linear array, the effective aperture of the array is $D_{array} = ND$ and the max gain:

$$G_{max} = \left(\frac{4\pi}{\lambda^2}\right) e_{max} D^2_{array} \tag{6}$$

- By replacing the latter formula into eq.(3) and assuming the array is used in both TX and RX:

$$P_r = \frac{P_t e_t e_r (D_r D_t)^2}{Losses(\lambda d)^2} \tag{7}$$

Antenna gain

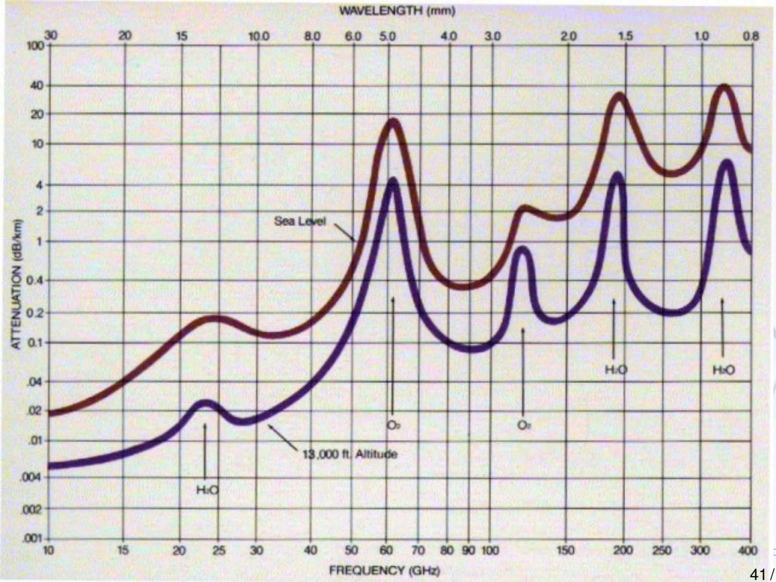
A twofold consideration:

According to eq.(7) one can say:

- The antenna array dimensions at the TX and RX (see D_r and D_t at the numerator in eq.(7)) can overcome the propagation path loss that is at the denominator.
- At mmWave, the small wavelengths make possible to fit more and more antennas into a small printed circuit resulting in gains significantly larger than the today's nearly omnidirectional cellphone antennas.

Outline

Atmospheric attenuation

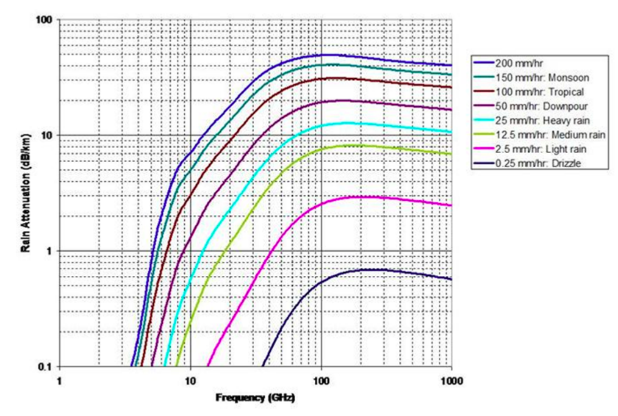


Atmospheric attenuation

Wireless propagation is significantly affected by atmospheric and molecular absorption according to frequency of em waves.

- The atmospheric attenuation of radio waves varies significantly with frequency.
- At the microwave frequency bands of up to 38 GHz, the attenuation due to the atmosphere at sea level is low at 0.3 dB/km or less.
- At 60 GHz (V-band), oxygen molecules let absorption increases up to 15 dB/km, limiting significantly radio transmission distance.
- A clear atmospheric window can be seen in the spectrum from around 70 GHz to 100 (E-band) GHz that results in low atmospheric attenuation around 0.5 dB/km occurs.

Rain attenuation



mm-wave transmissions can experience significant rain attenuation in the presence of rain that limits the maximum link length.

Outline

V-band vs E-band

	E-band	V-band
Regulation implications	Lightly licensed Simple registration required Small license fee Interference protection scheme	Unlicensed No registration No license fee Stealth mode
Distance implications	Subject to rain attenuation Several miles / kilometers	Subject to rain AND oxygen attenuation Up to 1600-2200 feet/500–700 meters
Form factor implications	Compact, dictated by typical 1 ft antenna Suitable for rooftops, towers and masts	Tiny Blends on the street level: building walls, light poles, bus stations, traffic lights
Applications	Fiber extension for businesses Macro backhaul Small cell backhaul in some particular cases Aggregation	Security (CCTV, traffic radars) WiFi backhaul Small cell backhaul GTTH – Fiber extension to customer premises

E-band technology

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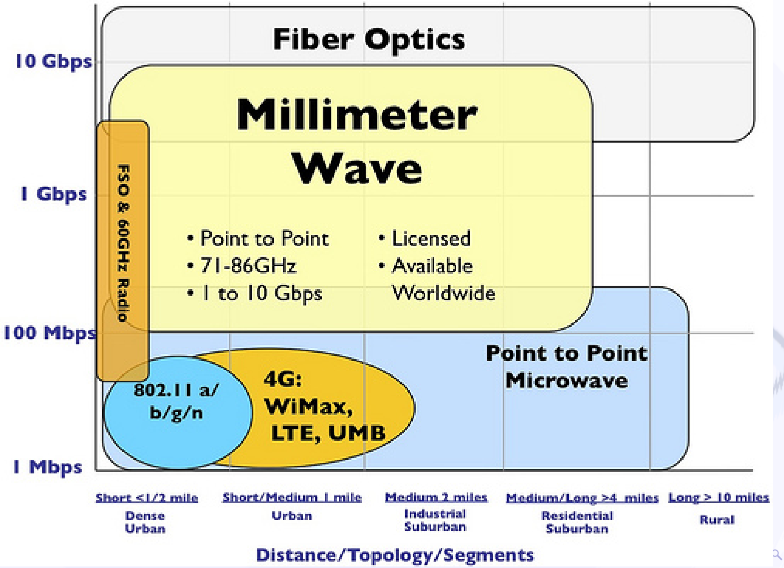
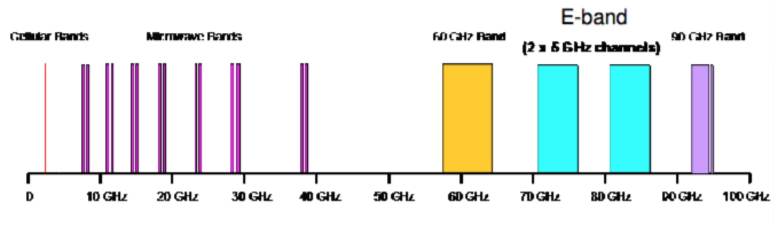
F. Nunziata



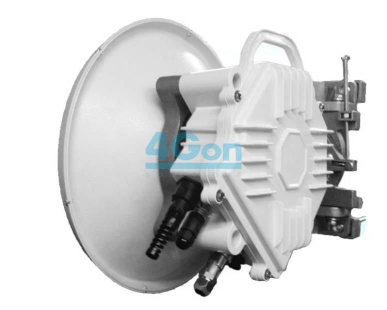
E-band technology



- E-band allocation consists of the two unchannelized bands of 71-76 GHz and 81-86 GHz.
- The combined 10 GHz of spectrum is significantly larger than any other frequency allocation.
- E-band allocation, divided into two paired 5 GHz channels, is not further partitioned (as is the case in the lower frequency microwave bands).
- Gigabit of data can be transmitted with simple modulation schemes.

E-band technology

Large gains can be obtained using relatively small antennas



The world's first commercially available 10 Gigabit wireless link is currently available for shipment as a capital equipment purchase or lease to customers worldwide.

mm-wave will allow service providers to drastically expand the channel bandwidths far beyond the 20 Mhz that characterizes 4G. Bandwidth of 5GHz are possible!

Operational scenarios

Innovative spectrum usage:

- 700 MHz for large area coverage;
- 3.6 to 3.8 GHz for medium capacity / coverage;
- mmWave bands for high capacity spot coverage;
- mmWave bands fronthaul / backhaul for difficult to reach locations using enhanced antenna technology capability, where wired (e.g. fiber) deployment is not economically viable;
- Hybrid solutions.

Outline

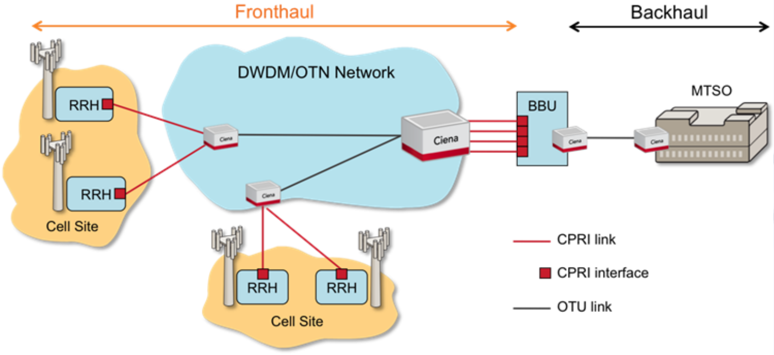
E-band technology for backhaul

There is growing interest among mobile operators in using the 80 GHz ‘millimeter wave’ frequencies to provide backhaul for LTE networks at urban and other traffic hotspots. This band has several attractions in this regard:

- Very high capacities can be supported, albeit over limited distances.
- A high degree of frequency reuse is possible, allowing a dense configuration of links without interference issues.
- A light licensing regime is used in many countries, making links cheap and quick to obtain.

Backhaul vs Fronthaul

A Baseband Unit (BBU) processes and controls data while the Radio Unit (RU) generates radio signals transmitted via tower-mounted antennas.



Backhaul vs Fronthaul

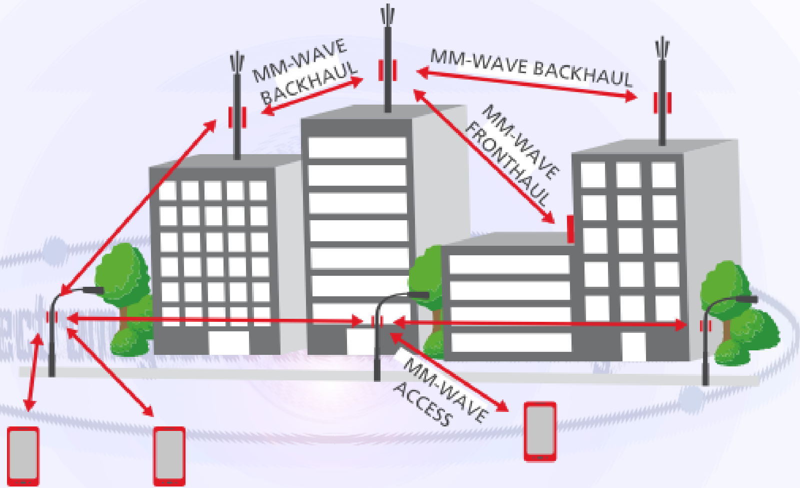
Backhaul

In its simplest form, backhaul connects the mobile network to the wired network by backhauling traffic from geographically dispersed cell sites to Mobile Switching Telephone Offices (MTSOs).

Fronthaul is a new Radio Access Network (RAN) architecture

In the fronthaul model, the RU equipment is now referred to as a Remote Radio Head (RRH) but is still located at the cell site. The BBU is now relocated to centralized and protected location where it serves multiple RRHs. The optical links that interconnect the newly centralized BBU and the multiple RRHs is referred to as fronthaul.

mmW Backhaul and Fronthaul



Outline

5g tourism

Metnet 60G	
Frequency band	60GHz mmWave unlicensed Full 57GHz to 71GHz band
Topologies	MultiPoint-to-MultiPoint (MPtMP) mesh Point-to-MultiPoint (PtMP) Point-to-Point (PtP)
Capacity	12Gbps per Node
Radio access	Metnet SON utilizing S-TDMA Dynamic TDD Self-organising zero frequency planning, interference aware with time and frequency switching agility
Beamwidth	Wide 300° field of view
Antennas	Beamforming Phase array 16x2 element arrangement 20dBi gain per antenna
Channels	Multiple 2160MHz wide channels 802.11ad Wi-Gig compliant
Modulation and coding	13 levels of adaptive encoding
Transmitter	20dBm SiGE based
Effective radiated power	40dBm per sector
Range	300m at MCS10 (3Gbps)
Interfaces	Up to 4 Ethernet interfaces 2 x fixed RJ45 100/1000 Base-T 2 x optional 10Gbps SFP (Optical or Electrical)
Ethernet services	Native Ethernet 802.1Q (VLAN tagging) 802.1p (Class of service) Differentiated Services Code Point (DSCP) 802.1ad (QinQ)
Power	100V - 240V AC / 50 - 60Hz 48V DC and PoE (1 x PD interface IEEE 802.3bt)
Dimensions	Height: 265mm, Diameter : 150mm (Max)
Weight	3.5 kg

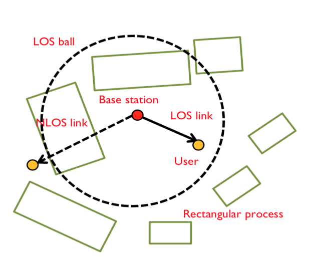
5g tourism

Cambridge Communication Systems (CCS) has provided its Metnet 60G unlicensed mmWave wireless solution for the UK backed 5G Smart Tourism project in the historic city of Bath.

- CCSs' Metnet 60G delivers up to 12Gbps per radio, providing gigabit backhaul to support interactive 5G smart tourism applications and enhanced visual experiences using augmented reality (AR) and virtual reality (VR) technology.
- The AR and VR content and technology capabilities will be provided by the BBC and Aardman with support from the University of Bristol's Smart Internet Lab.

Channel issues

Obstacles in the environment affect wireless communication channels owing to reflection, diffraction, scattering, absorption, and refraction.



A key aspect that characterizes 5g is the blocking, e.g.; penetration losses through buildings can be as high as 40 – 80 dB!

Penetration losses

Measured penetration losses of common building materials @ mmW

Reference	*Frequency (GHz)*	*Location*	*Material Description*	*Thickness (cm)*	*Penetration Loss (dB)*
Rappaport et al. (2013b)	28	Exterior	Tinted glass	3.8	40.1
			Brick pillar	185.4	28.3
		Interior	Clear glass	<1.3	3.9
			Tinted glass	<1.3	24.5
			Wall	38.1	6.8
Xu et al. (2000)	38	Exterior	Double-pane, tampered tinted glass	–	25.5
Moraitis and Constantinou (2004)	60	Interior	Double glass	1.5	4.5
			Simple glass	0.5	3.5
			Whiteboard	1.5	11.6
			Plywood panels	0.5	6
		Exterior	Brick wall with plasterboard	23	48

Indoor vs outdoor

Outdoor –> indoor

- Buildings are almost impenetrable from outdoor access links; hence it is infeasible to achieve indoor coverage from outdoor base stations.
- Indoor-to-outdoor coverage is only possible either using relays and repeaters or else outdoor mobile users will need to hand-off into the indoor network (perhaps unlicensed spectrum or reused mm-Wave spectrum) as a user enters a building.

Indoor vs outdoor

Indoor –> outdoor

- Indoor-to-outdoor penetration is also impractical in mm-Wave frequencies.
- Indoor hotspots are actually isolated.

The lower penetration loss of indoor materials in conjunction with the reflective and high loss outdoor materials (brick walls and glass) helps reduce interference between indoor and outdoor mm-Wave networks, suggesting a high frequency reuse.

LOS probability model

It is worth distinguishing the LOS and NLOS links using a stochastic model.

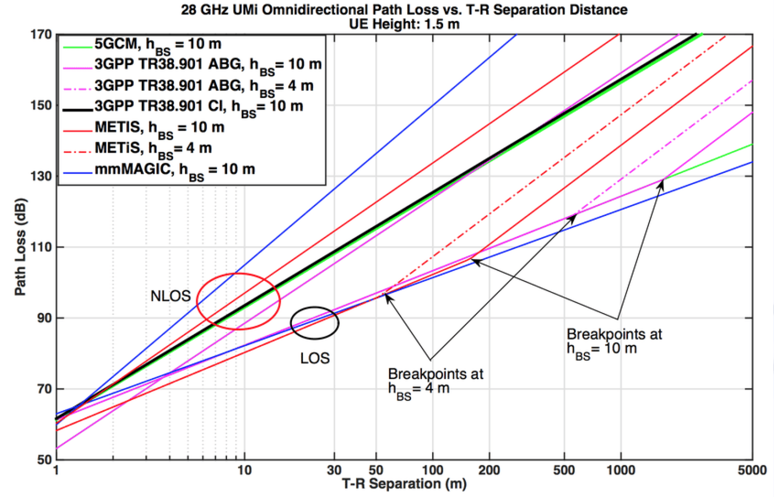
- Statistical models are needed to predict the likelihood that a user equipment is within a clear LOS of the TX or in a NLOS region due to obstructions.
- LOS propagation will offer more reliable performance in mmWave communication. In fact, diffraction loss increases with frequency as well as path loss exponent and shadowing variance.
- There are several models to model LOS probability that do not depend on frequency and rely on the 2D TX-RX distance.

Large scale path loss models

There are three basic types of large-scale path loss models to predict mmWave signal strength over distance for the vast mmWave frequency range:

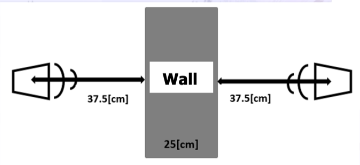
- The close-in free space reference distance (CI) path loss model (with a 1 m reference distance).
- The CI model with a frequency-weighted (CIF model) or height-weighted (CIH model) path loss exponent.
- The ABG model.

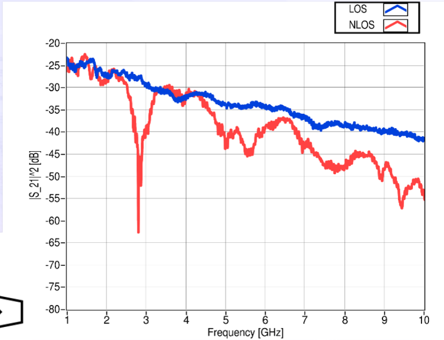
Path loss models



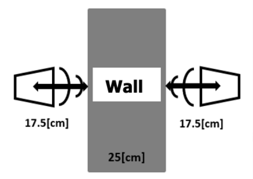
Outline

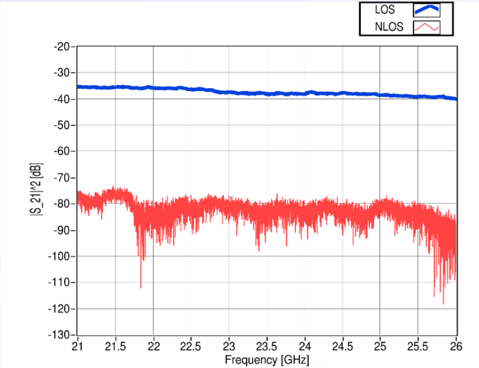
Penetration loss



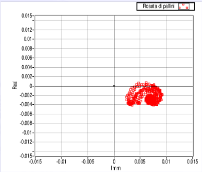


Penetration loss





Multipath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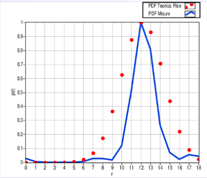
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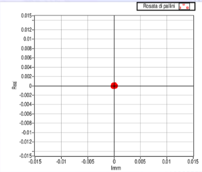
Rosata di pallini
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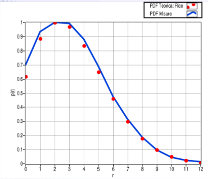
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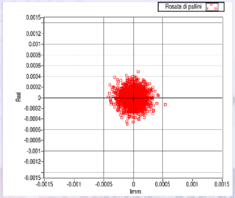
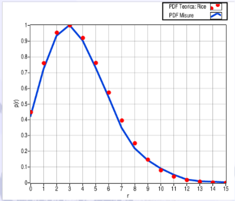
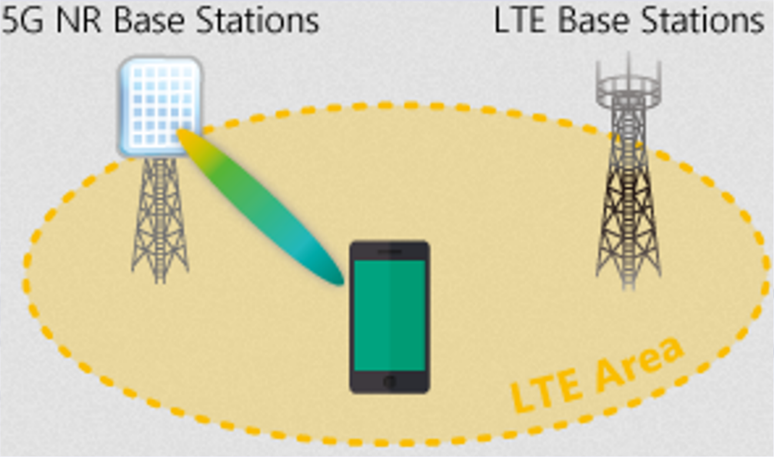
Multipath



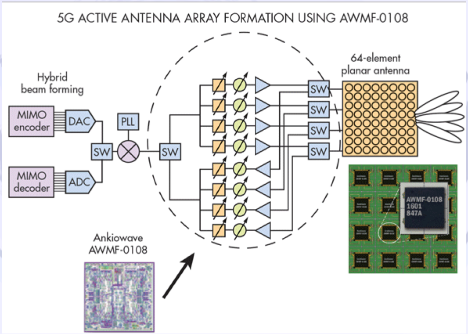


Directive antennas



Adaptive arrays

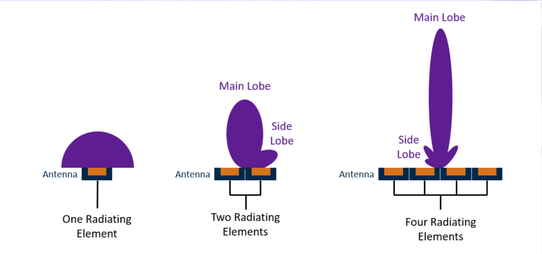
Beam steerable antenna technologies are a key tool since they allow estimating the direction of arrival and adaptively switch beam patterns to mitigate interference and to capture the signal of interest.



Beam-forming

Arrays of radiating antenna elements

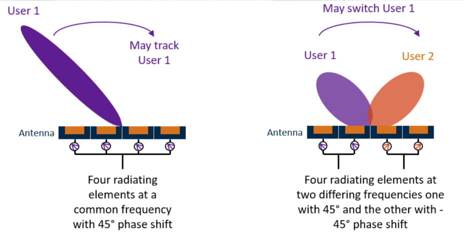
Beamforming is the application of multiple radiating elements transmitting the same signal at an identical wavelength and phase, which combine to create a single antenna with a longer, more targeted stream which is formed by reinforcing the waves in a specific direction.



Beam steering

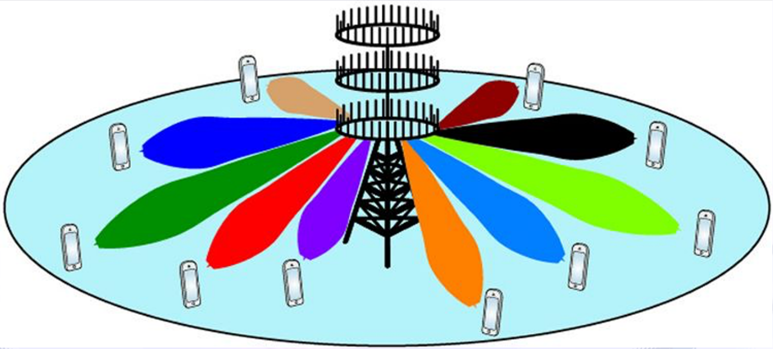
Arrays of radiating antenna elements

Beam steering is achieved by changing the phase of the input signal on all radiating elements. Phase shifting allows the signal to be targeted at a specific receiver. An antenna can steer a single frequency beam or different frequency beams in different directions to serve different users.



The direction a signal is sent in is calculated dynamically by the base station as the endpoint moves, effectively tracking the user.

Beamforming & beamtracking



Beamforming & beamtracking

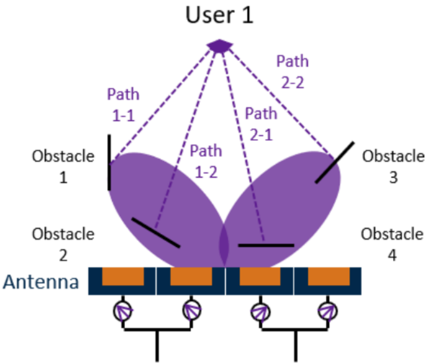
Massive MIMO

Multiple Input Multiple Output

MIMO antennas have long been a feature of commercial public wireless and Wi-Fi systems, but 5G demands the application of massive MIMO.
To increase the SNR of a transmitted signal and the channel capacity, without increasing spectrum usage, a common frequency can be steered simultaneously in multiple directions.

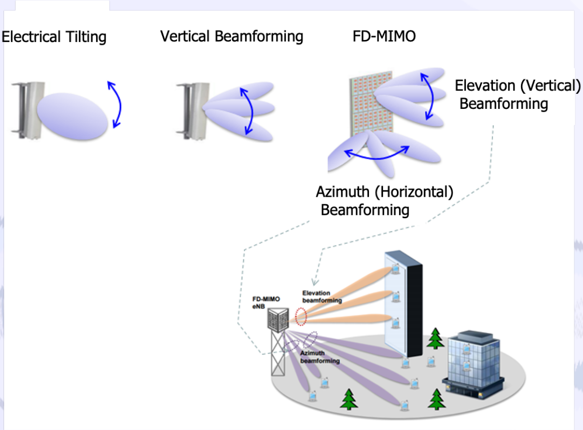
The successful operation of MIMO systems requires the implementation of powerful digital signal processors and an environment which is rich diversity of signal paths between the transmitter and the receiver.

Massive MIMO



Four Radiating Elements at a common frequency with 45° the other with -45° phase shift supporting MIMO for increasing SNR and channel capacity

Smart antennas: in a nutshell



For further reading

- T.S. Rappaport et al. “Millimiter wave wireless communications,” Prentice Hall 2015.
- Discussion paper: “5g Spectrum and Neutral Hosting”, 2019.