ECE6604
PERSONAL & MOBILE COMMUNICATIONS

GORDON L. STÜBER

School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332-0250
Ph: (404) 894-2923
Fax: (404) 894-7883
E-mail: stuber@ece.gatech.edu
URL: http://www.ece.gatech.edu/users/stuber/6604

COURSE OBJECTIVES

- The course treats the underlying principles of mobile communications that are applicable to a wide variety of wireless systems and standards.
    - Focus is on the physical layer (PHY), medium access control layer (MAC), and connection layer.
    - Consider elements of digital baseband processing as opposed to analog radio frequency (RF) processing.
- Mathematical modeling, statistical characterization and simulation of wireless channels, signals, noise and interference.
- Design of digital waveforms and associated receiver structures for recovering channel corrupted message waveforms.
    - Single-carrier and multi-carrier signaling schemes and their performance analysis on wireless channels.
    - Methods for mitigating wireless channel impairments and co-channel interference.
- Architectures and deployment of wireless systems, including link budget and frequency planning.

TOPICAL OUTLINE

1. INTRODUCTION TO CELLULAR RADIO SYSTEMS
2. MULTIPATH-FADING CHANNEL MODELLING AND SIMULATION
3. SHADOWING AND PATH LOSS
4. CO-CHANNEL INTERFERENCE AND OUTAGE
5. SINGLE- AND MULTI-CARRIER MODULATION TECHNIQUES AND THEIR POWER SPECTRUM
6. BASIC DIGITAL SIGNALING ON FLAT FADING CHANNELS
7. MULTI-ANTENNA TECHNIQUES
8. MULTI-CARRIER TECHNIQUES

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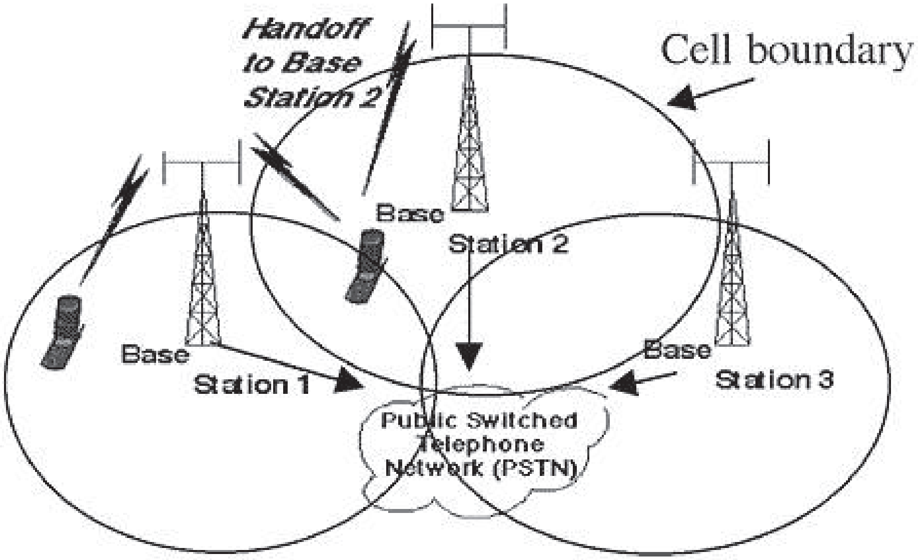
Week 1

Introduction,
Path Loss, Co-channel Interference

Reading: Chapter 1, 1.1-1.4, Chapter 11, 11.1

CELLULAR CONCEPT



- Base stations (BSs) transmit to and receive from mobile stations (MSs) using assigned licensed spectrum.

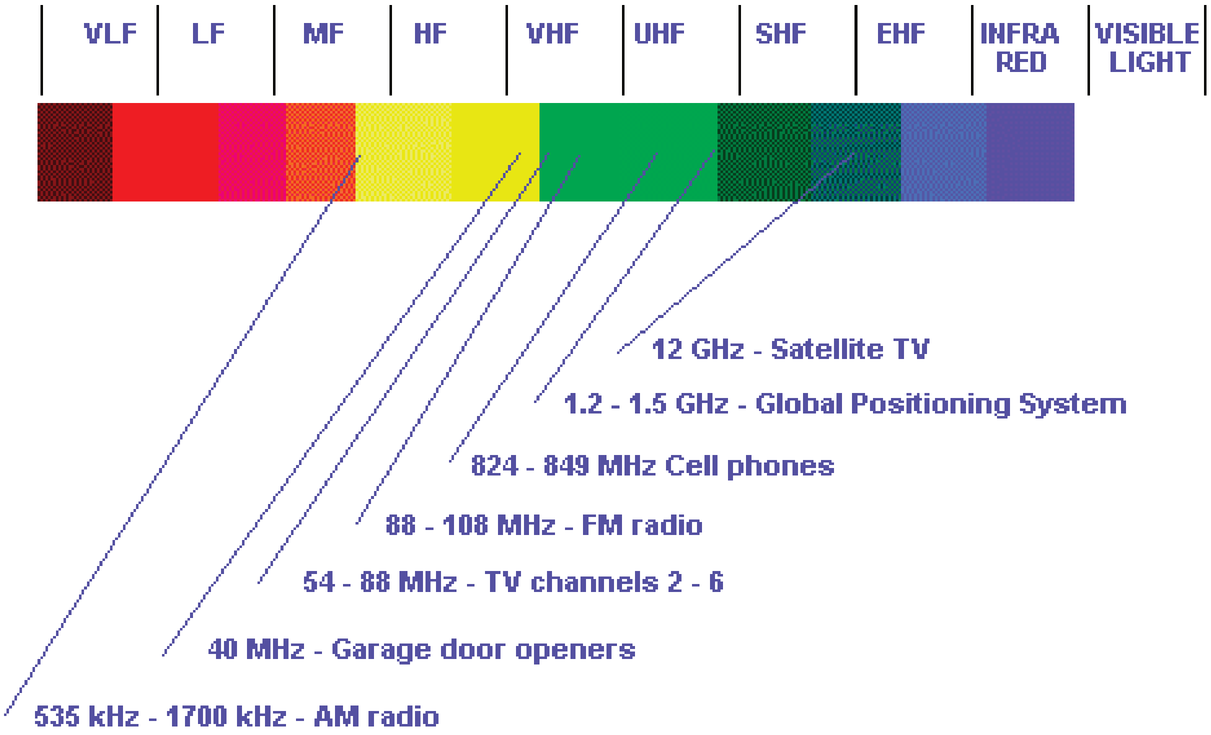
- Multiple BSs use the same spectrum (frequency reuse).

- The service area of each BS is called a “cell.”

- Each MS is typically served by the “closest” BSs.

- Handoffs or handovers occur when MSs move from one cell to the next.

CELLULAR FREQUENCIES



Cellular frequencies (USA):

700MHz: 698-806 (3G, 4G, MediaFLO (defunct), DVB-H)
GSM800: 806-824, 851–869 (SMR iDEN, CDMA (future), LTE (future))
GSM850: 824-849, 869-894 (GSM, IS-95 (CDMA), 3G)
GSM1900 or PCS: 1,850-1,910, 1,930-1,990 (GSM, IS-95 (CDMA), 3G, 4G)
AWS: 1,710-1,755, 2,110–2,155 (3G, 4G)
BRS/EBS: 2,496-2,690 (4G)
600MHz: 84 MHz, 10 MHz unlicensed (incentive auction)

Cellular Technologies

- 0G: Briefcase-size mobile radio telephones (1970s)
- 1G: Analog cellular telephony (1980s)
- 2G: Digital cellular telephony (1990s)
- 3G: High-speed digital cellular telephony, including video telephony (2000s)
- 4G: All-IP-based anytime, anywhere voice, data, and multimedia telephony at faster data rates than 3G (2010s)
- 5G: Gbps, low latency, wireless based on mm-wave small cell technology, massive MIMO, heterogeneous networks (2020s).

0G and 1G Cellular

- 1979 — Nippon Telephone and Telegraph (NTT) introduces the first cellular system in Japan.
- 1981 — Nordic Mobile Telephone (NMT) 900 system introduced by Ericsson Radio Systems AB and deployed in Scandinavia.
- 1984 — Advanced Mobile Telephone Service (AMPS) introduced by AT&T in North America.

2G Cellular

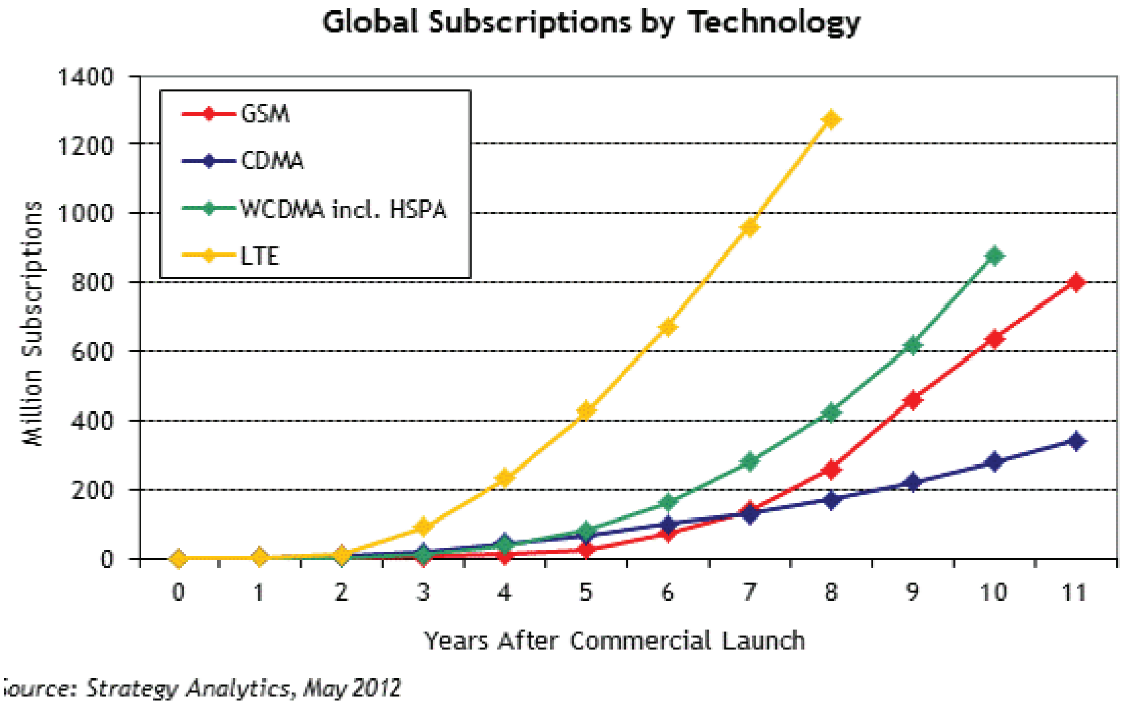
- 1987 — Europe produces very first agreed GSM Technical Specification
- 1990 — Interim Standard IS-54 (USDC) standardized by TIA.
- 1991 — Japanese Ministry of Posts and Telecommunications standardizes Personal Digital Cellular (PDC)
- 1993 — Interim Standard IS-95A (CDMA) standardized by TIA.
- 1994 — Interim Standard IS-136 standardized by TIA.
- 1998 — IS-95B standardized by TIA.
- 1998 — GSM Phase 2+ (GPRS) standardized by ETSI.

3G Cellular

- 2000 — South-Korean Telecom (SKT) launches cdma2000-1X network (DL/UL: 153 kbps)
- 2001 — NTT DoCoMo deploys commercial UMTS network in Japan
- 2002 — cdma2000 1xEV-DO (UL: 153 kbps, DL: 2.4 Mb/s)
- 2003 — WCDMA (UL/DL: 384 kbps)
- 2006 — HSDPA (UL: 384 kbps, DL: 7.2 Mbps)
- 2007 — cdma2000 1xEV-DO Rev A (UL: 1.8 Mbps, DL: 3.1 Mbps)
- 2010 — HSDPA/HSUPA (UL: 5.8 Mbps, DL: 14.0 Mbps), cdma2000 1xEV-DO Rev A (UL: 1.8 Mbps, DL: 3.1 Mbps)

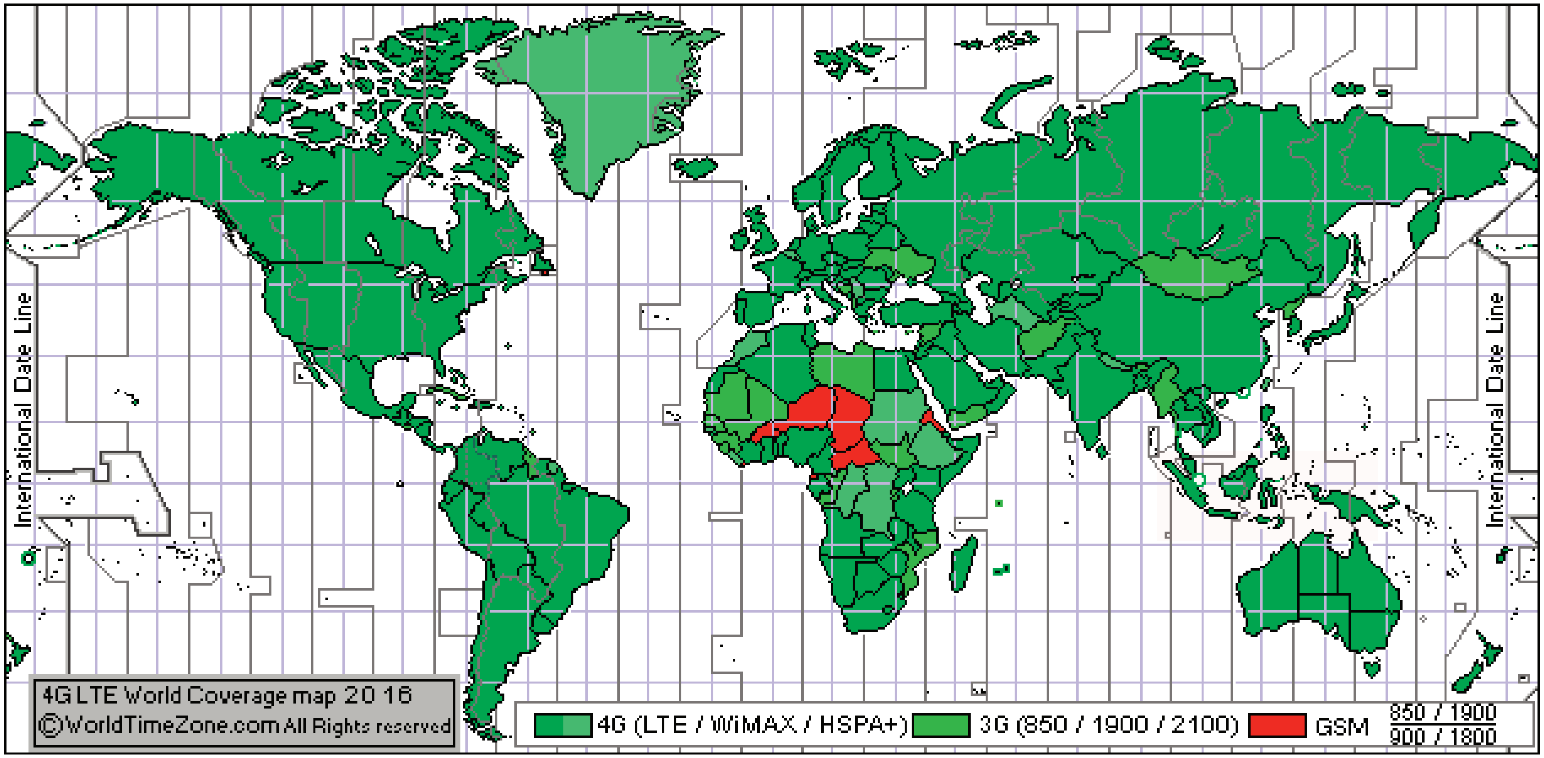
4G Cellular

- LTE: Seeing rapid deployment (DL 299.6 Mbit/s, UL 75.4 Mbit/s)
  - There are 585 LTE networks in 189 countries
  - 3.1 billion subscribers worldwide 2018, 4 billion 2019.
- LTE-A: is a true 4G system (DL 3 Gbps, UL 1.5 Gbps)
  - There are 233 LTE-A networks.
- VoLTE in 239 networks in 111 countries; 610 million subscribers.
- 9 billion mobile subscriptions by 2022 with 8.3 billion smartphone users, 6.2 billion unique mobile subscribers.
- 1.5 billion IoT devices with cellular connections by 2022 (total 29 billion connected IoT devices).



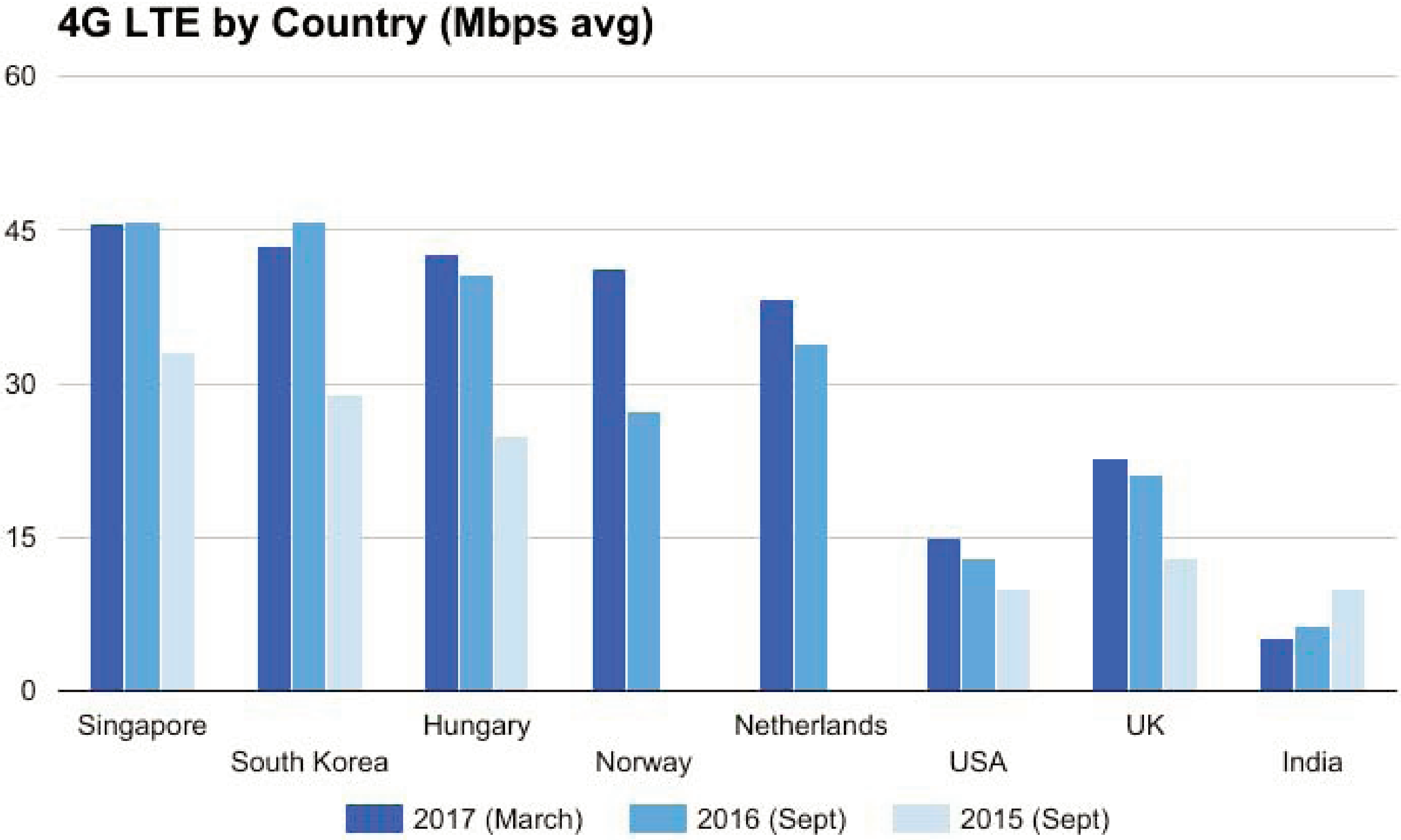
ource: Strategy Analytics, May 2012

Cellular growth rates by technology.



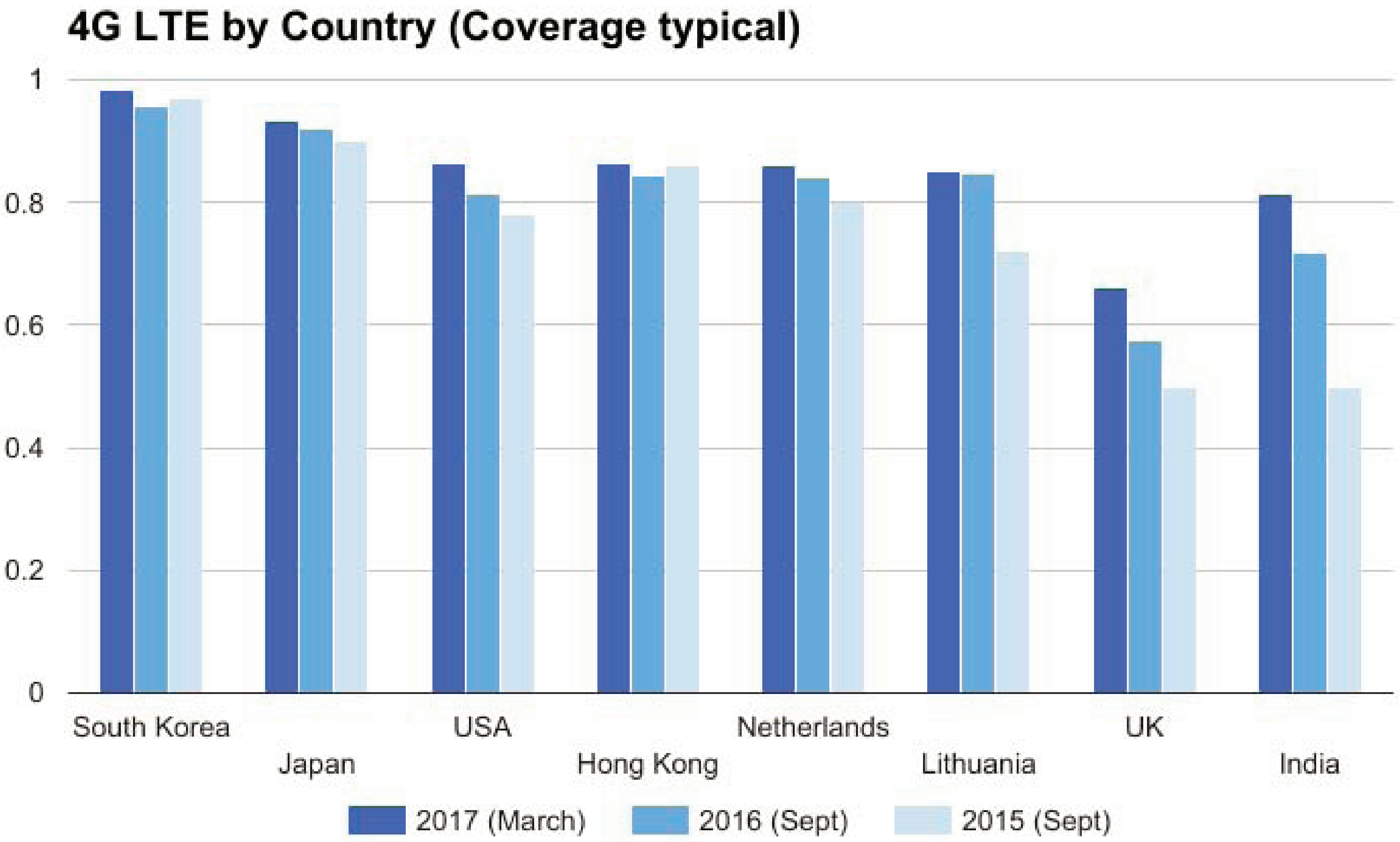
4G Cellular Deployment Worldwide.

World's Fastest 4G Networks



Robert Triggs, "State of the worlds 4G LTE networks June 2017," Android Authority

World's Best Coverage with 4G



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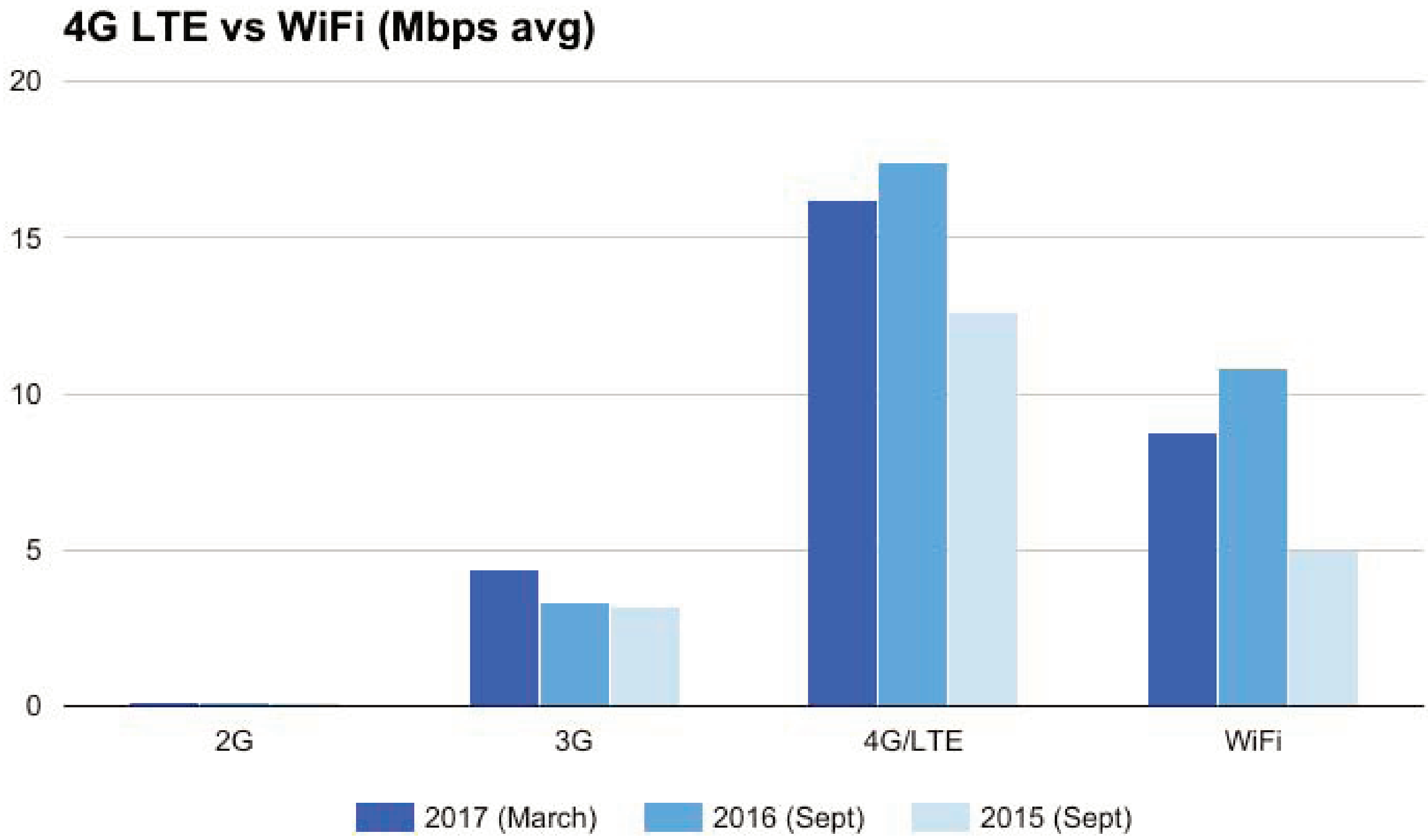
World Broadband Coverage



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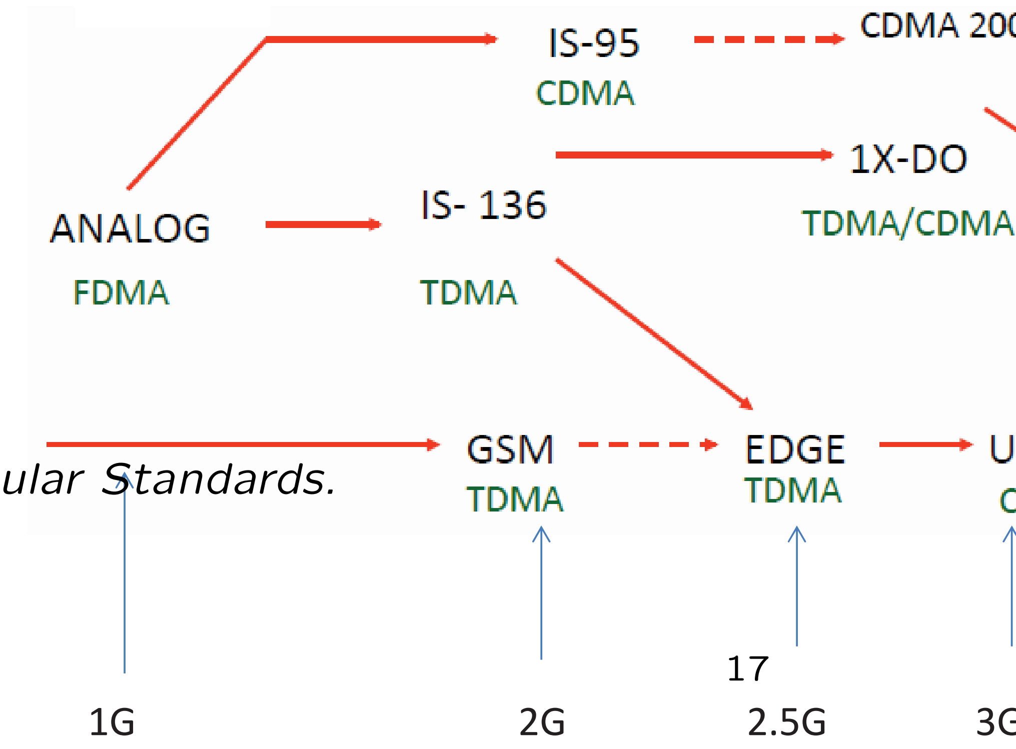


Evolution of Cellular Standards.

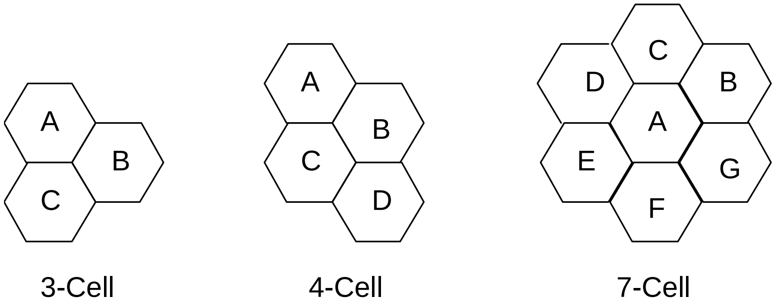
5G Cellular

- 1000 times more data volume than 4G.
- 10 to 100 times faster than 4G with an expected speed of 1 to 10 Gbps.
- 10-100 times higher number of connected devices.
- 5 times lower end-to-end latency (1 ms delay).
- 10 times longer battery life for low-power devices.

5G Cellular Enabling Technologies

- Massive MIMO
- Ultra-Dense Networks
- Moving Networks
- Higher Frequencies (mm-wave)
- D2D Communications
- Ultra-Reliable Communications
- Massive Machine Communications

FREQUENCY RE-USE AND THE CELLULAR CONCEPT



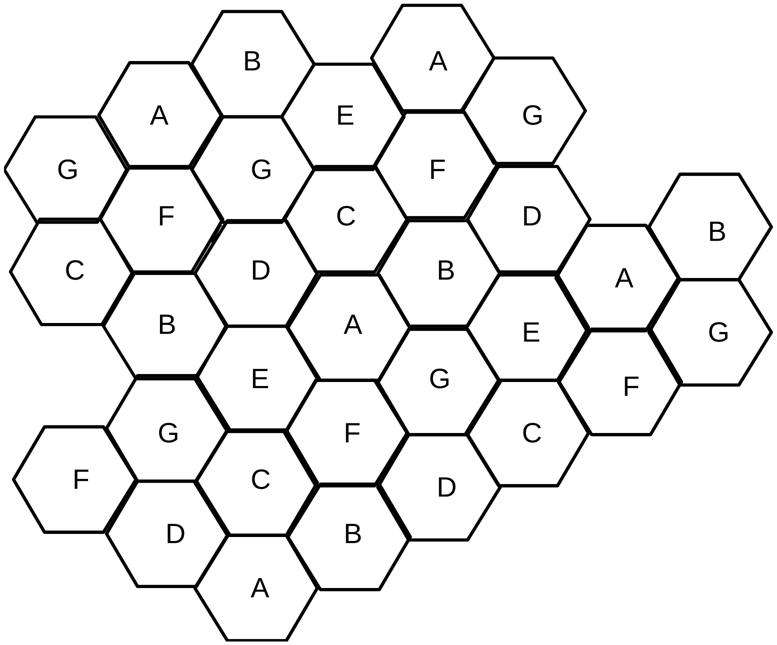
Commonly used hexagonal cellular reuse clusters.

- Tessellating hexagonal cluster sizes, N, satisfy

$$N = i^2 + ij + j^2$$

where $i,\ j$ are non-negative integers and $i \geq j$.

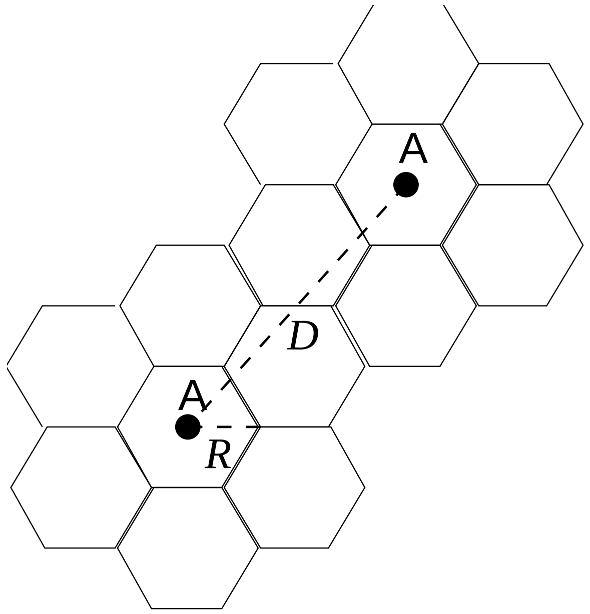
  - hence $N = 1,\ 3,\ 4,\ 7,\ 9,\ 12, \ldots$ are allowable.



Cellular layout using 7-cell reuse clusters.

- Real cells are not hexagonal, but irregular and overlapping.
- Frequency reuse introduces **co-channel interference** and **adjacent channel interference**.

CO-CHANNEL REUSE FACTOR



Frequency reuse distance for 7-cell reuse clusters.

- For hexagonal cells, the co-channel reuse factor is

$$\frac{D}{R} = \sqrt{3N}$$

RADIO PROPAGATION MECHANISMS

- Radio propagation is by three mechanisms:
    - **Reflections** off of objects larger than a wavelength, sometimes called scatterers.
    - **Diffractions** around the edges of objects
    - **Scattering** by objects smaller than a wavelength
- A mobile radio environment is characterized by three nearly independent propagation factors:
    - **Path loss** attenuation with distance.
    - **Shadowing** caused by large obstructions such as buildings, hills and valleys.
    - **Multipath-fading** caused by the combination of multipath propagation and transmitter, receiver and/or scatterer movement.

FREE SPACE PATH LOSS (FSPL)

- Equation for free-space path loss is

$$L_{\mathsf{FS}} = \left(\frac{4\pi d}{\lambda_c}\right)^2 \quad .$$

  and encapsulates two effects.

  1. The first effect is that spreading out of electromagnetic energy in free space is determined by the inverse square law, i.e.,

     $$\mu_{\Omega_r}(d) = \Omega_t \frac{1}{4\pi d^2} \quad ,$$

     where

     - Ω_t is the transmit power
     - $\mu_{\Omega_r}(d)$ is the received power per unit area or power spatial density (in watts per meter-squared) at distance d. Note that this term is not frequency dependent.

FREE SPACE PATH LOSS (FSPL)

- Second effect

  2. The second effect is due to aperture, which determines how well an antenna picks up power from an incoming electromagnetic wave. For an isotropic antenna, we have

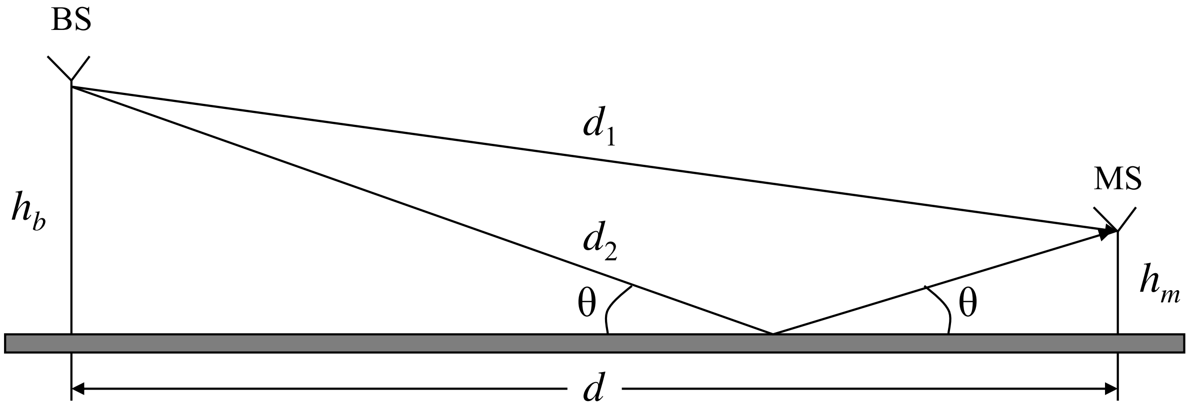
  $$\mu_{\Omega_p}(d) = \mu_{\Omega_r}(d)\frac{\lambda_c^2}{4\pi} = \Omega_t\left(\frac{\lambda_c}{4\pi d}\right)^2 \quad ,$$

     where $\mu_{\Omega_p}(d)$ is the received power. Note that aperature is entirely dependent on wavelength, λ_c, which is how the frequency-dependent behavior arises in the free space path loss.

- The free space propagation path loss is

$$\begin{aligned} L_{\text{FS (dB)}} = 10\log_{10}\left\{\frac{\Omega_t}{\mu_{\Omega_p}(d)}\right\} &= 10\log_{10}\left\{\left(\frac{4\pi d}{\lambda_c}\right)^2\right\} \\ &= 10\log_{10}\left\{\left(\frac{4\pi d}{c/f_c}\right)^2\right\} \\ &= 20\log_{10}f_c + 20\log_{10}d - 147.55 \text{ dB} \quad . \end{aligned}$$

PROPAGATION OVER A FLAT SPECULAR SURFACE



- The length of the direct path is

$$d_1 = \sqrt{d^2 + (h_b - h_m)^2}$$

and the length of the reflected path is

$$d_2 = \sqrt{d^2 + (h_b + h_m)^2}$$

d = distance between mobile and base stations
h_b = base station antenna height
h_m = mobile station antenna height

- Given that $d \gg h_b h_m$, we have $d_1 \approx d$ and $d_2 \approx d$.

- However, since the wavelength is small, the direct and reflected paths may add constructively or destructively over small distances. The carrier phase difference between the direct and reflected paths is

$$\phi_2 - \phi_1 = \frac{2\pi}{\lambda_c}(d_2 - d_1) = \frac{2\pi}{\lambda_c}\Delta_d$$

- Taking into account the phase difference, the received signal power is

$$\mu_{\Omega_p}(d) = \Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 \left|1 + a e^{-jb} e^{j\frac{2\pi}{\lambda_c}\Delta_d}\right|^2 \quad ,$$

  where a and b are the amplitude attenuation and phase change introduced by the flat reflecting surface.

- If we assume a perfect specular reflection, then $a = 1$ and $b = \pi$ for small θ. Then

$$\begin{aligned}
\mu_{\Omega_p}(d) &= \Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 \left|1 - e^{j\left(\frac{2\pi}{\lambda_c}\Delta_d\right)}\right|^2 \\
&= \Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 \left|1 - \cos\left(\frac{2\pi}{\lambda_c}\Delta_d\right) - j\sin\left(\frac{2\pi}{\lambda_c}\Delta_d\right)\right|^2 \\
&= \Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 \left[2 - 2\cos\left(\frac{2\pi}{\lambda_c}\Delta_d\right)\right] \\
&= 4\Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 \sin^2\left(\frac{\pi}{\lambda_c}\Delta_d\right)
\end{aligned}$$

- Given that $d \gg h_b$ and $d \gg h_m$, and applying the Taylor series approximation $\sqrt{1+x} \approx 1 + x/2$ for small x, we have

$$\Delta_d \approx d\left(1+\frac{(h_b+h_m)^2}{2d^2}\right) - d\left(1+\frac{(h_b-h_m)^2}{2d^2}\right) = \frac{2h_bh_m}{d} \quad .$$

- This approximation yields the received signal power as

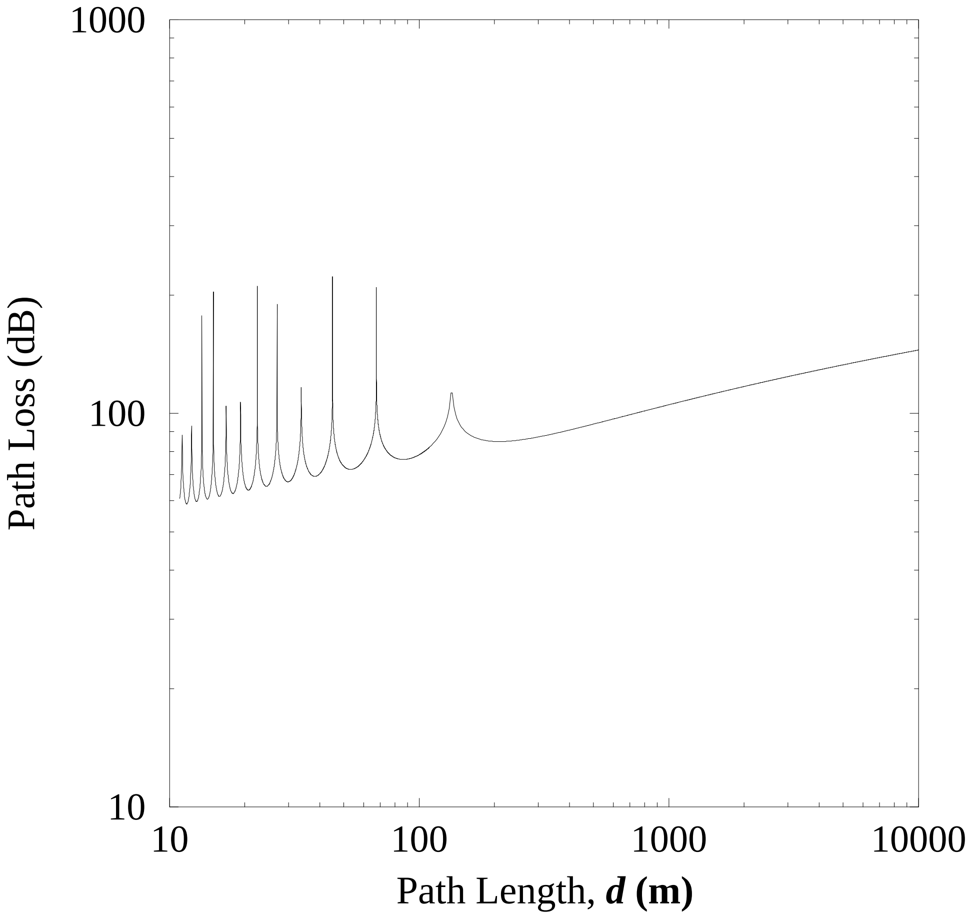
$$\mu_{\Omega_p}(d) \approx 4\Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 \sin^2\left(\frac{2\pi h_b h_m}{\lambda_c d}\right)$$

- Often we will have the condition $d \gg h_b h_m$, such that the above approximation further reduces to

$$\mu_{\Omega_p}(d) \approx \Omega_t \left(\frac{h_b h_m}{d^2}\right)^2$$

  where we have invoked the small angle approximation $\sin x \approx x$ for small x.

- Propagation over a flat specular surface differs from free space propagation in two important respects
  - it is not frequency dependent
  - signal strength decays with the with the fourth power of the distance, rather than the square of the distance.



Propagation path loss $L_{p\ \text{(dB)}}$ with distance over a flat reflecting surface; $h_b = 7.5$ m, $h_m = 1.5$ m, $f_c = 1800\ MHz$.

$$L_{\text{FE (dB)}} = \left[\left(\frac{\lambda_c}{4\pi d} \right)^2 4 \sin^2 \left(\frac{2\pi h_b h_m}{\lambda_c d} \right) \right]^{-1}$$

- In reality, the earth's surface is curved and rough, and the signal strength typically decays with the inverse β power of the distance, and the received power at distance d is

  $$\mu_{\Omega_p}(d) = \frac{\mu_{\Omega_p(d_o)}}{(d/d_o)^\beta}$$

  where $\mu_{\Omega_p}(d_o)$ is the received power at a reference distance d_o.

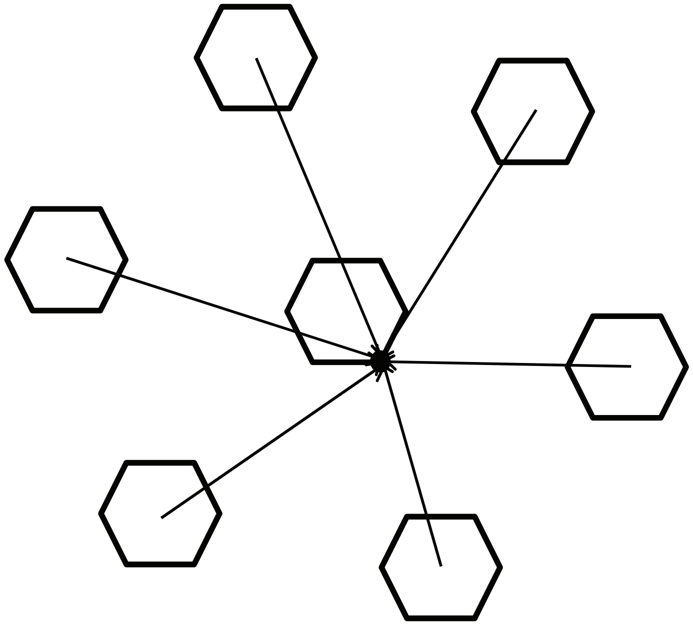
- Expressed in units of dBm, the received power is

  $$\mu_{\Omega_p \text{ (dBm)}}(d) = \mu_{\Omega_p \text{ (dBm)}}(d_o) - 10\beta \log_{10}(d/d_o) \quad \text{(dBm)}$$

- β is called the **path loss exponent**. Typical values of $\mu_{\Omega_p \text{ (dBm)}}(d_o)$ and β have been determined by empirical measurements for a variety of areas

Terrain	$\mu_{\Omega_p \text{ (dBm)}}(d_o = 1.6 \text{ km})$	β
Free Space	-45	2
Open Area	-49	4.35
North American Suburban	-61.7	3.84
North American Urban (Philadelphia)	-70	3.68
North American Urban (Newark)	-64	4.31
Japanese Urban (Tokyo)	-84	3.05

Co-channel Interference



Worst case co-channel interference on the forward channel.

Worst Case Co-Channel Interference

- For $N = 7$, there are six first-tier co-channel BSs, located at distances $\{\sqrt{13}R, 4R, \sqrt{19}R, 5R, \sqrt{28}R, \sqrt{31}R\}$ from the MS.

- Assuming that the BS antennas are all the same height and all BSs transmit with the same power, the worst case carrier-to-interference ratio, Λ, is

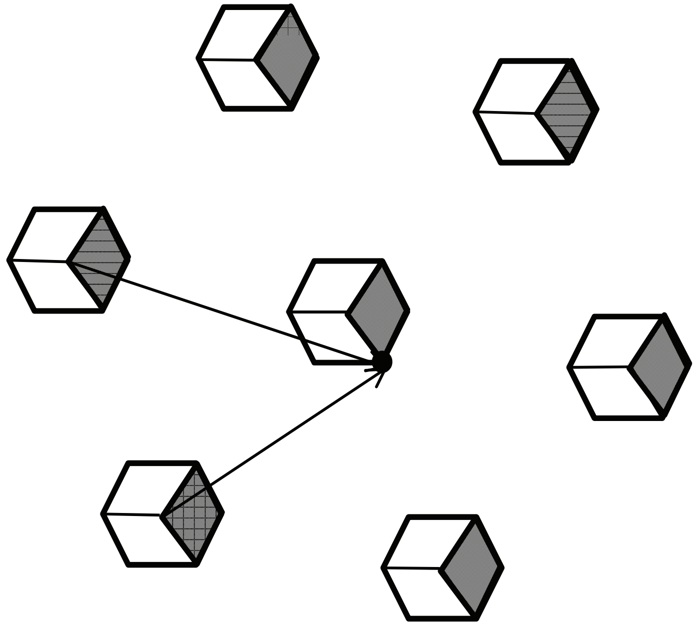
$$\begin{aligned}\Lambda &= \frac{R^{-\beta}}{(\sqrt{13}R)^{-\beta} + (4R)^{-\beta} + (\sqrt{19}R)^{-\beta} + (5R)^{-\beta} + (\sqrt{28}R)^{-\beta} + (\sqrt{31}R)^{-\beta}} \\ &= \frac{1}{(\sqrt{13})^{-\beta} + (4)^{-\beta} + (\sqrt{19})^{-\beta} + (5)^{-\beta} + (\sqrt{28})^{-\beta} + (\sqrt{31})^{-\beta}} \quad .\end{aligned}$$

- With a path loss exponent $\beta = 3.5$, the worst case Λ is

$$\Lambda_{(\text{dB})} = \begin{cases} 14.56 \text{ dB} & \text{for } N = 7 \\ 9.98 \text{ dB} & \text{for } N = 4 \\ 7.33 \text{ dB} & \text{for } N = 3 \end{cases} \quad .$$

  - Shadows will introduce variations in the worst case Λ.

Cell Sectoring



Worst case co-channel interference on the forward channel with 120° cell sectoring.

- 120$^\text{o}$ cell sectoring reduces the number of co-channel base stations from six to two. For $N = 7$, the two first tier interferers are located at distances $\sqrt{19}R, \sqrt{28}R$ from the MS.

- The carrier-to-interference ratio becomes

$$\begin{aligned} \Lambda &= \frac{R^{-\beta}}{(\sqrt{19}R)^{-\beta} + (\sqrt{28}R)^{-\beta}} \\ &= \frac{1}{(\sqrt{19})^{-\beta} + (\sqrt{28})^{-\beta}} \quad . \end{aligned}$$

- Hence

$$\Lambda_{(\text{dB})} = \begin{cases} 20.60 \text{ dB} & \text{for } N = 7 \\ 17.69 \text{ dB} & \text{for } N = 4 \\ 13.52 \text{ dB} & \text{for } N = 3 \end{cases} \quad .$$

- For $N = 7$, 120$^\text{o}$ cell sectoring yields a 6.04 dB C/I improvement over omni-cells.

- The minimum allowable cluster size is determined by the threshold Λ, Λ_{th}, of the radio receiver. For example, if the radio receiver has $\Lambda_{\text{th}} = 15.0$ dB, then a 4/12 reuse cluster can be used (4/12 means 4 cells or 12 sectors per cluster).