ECE 5325/6325: Wireless Communication Systems
Lecture Notes, Spring 2013

Lecture 1

Today: (1) Syllabus, (2) Cellular Systems Intro, (3) Power and Path Loss

- Readings: Molisch Chapters 1, 2. For Thursday: Molisch 17.6.
- Get a sticker on your ECE mailbox

1 Cellular Systems Intro

1.1 Generation Zero

The study of the history of cellular systems can help us understand the need for the system design concepts we have today.

One of the major developments in WWII was the miniaturization of FM radio components to a backpack or handheld device (the walkie-talkie), a half-duplex (either transmit or receive, not both) push-to-talk communication device. After returning from war, veterans had the expectation that wireless communications should be available in their civilian jobs [4]. But the phone system, the Public Switched Telephone Network (PSTN) was: wired, and manually switched at telephone exchanges. In 1952, the Mobile Telephone System (MTS) was designed to serve 25 cities in the US [3] (including one in Salt Lake City [2]). In each city, an additional telephone exchange office was created for purpose of connection with the mobile telephones [4]. The MTS and later the improved mobile telephone system (IMTS), introduced in 1964, were not particularly spectrally efficient.

- They were allocated a total bandwidth of about 2 MHz. Frequency modulation (FM) was used. For multiple user access, the system operated frequency division multiple access (FDMA), in which each channel was allocated a non-overlapping frequency band within the 2 MHz.
- The PTSN is full duplex (transmit and receive simultaneously) in IMTS, so it required two channels for each call, one uplink (to the base station) and one downlink (to the mobile receiver). Note MTS had been half duplex, *i.e.*, only one party could talk at once.
- The FCC required them to operate over an entire city (25 mile radius). Since the coverage was city wide, and coverage did not exist outside of the cities, there was no need for handoff.

- Initially channels were 120 kHz [1], due to poor out-of-band filtering. The channel bandwidth was cut to 60 kHz in 1950 and again to 30 kHz in 1965. Thus there were 2 MHz / 2 / 120 kHz or 8 full duplex channels at the start, and up to 32 in 1965, *for the entire city*.

Control was manual, and the control channel was open for anyone to hear. In fact, users were required to be listening to the control channel. When the switching operator wanted to connect to any mobile user, they would announce the call on the control channel. If the user responded, they would tell the user which voice channel to turn to. Any other curious user could listen as well. A mobile user could also use the control channel to request a call to be connected. The system was congested, so there was always activity.

The demand was very high, even at the high cost of about $400 per month (in 2009 dollars). There were a few hundred subscribers in a city [3] but up to 20,000 on the waiting list [4]. The only way to increase the capacity was to allocate more bandwidth, but satisfying the need would have required more bandwidth than was available.

The downsides to MTS took a significant amount of technological development to address, and the business case was not clear (AT&T developed the technologies over 35 years, but then largely ignored it during the 1980s when it was deployed [3]).

1.2 Cellular

The cellular concept is to partition a geographical area into “cells”, each covering a small fraction of a city. Each cell is allocated a “channel group”, *i.e.*, a subset of the total list of channels. A second cell, distant from a first cell using a particular channel group, can reuse the same channel group. This is called “frequency reuse”. This is depicted in Figures 17.11 and 17.2 in Molisch. This assumes that at a long distance, the signals transmitted in the first cell are too low by the time they reach the second cell to significantly interfere with the use of those channels in the second cell.

There are dramatic technical implications of the cellular concept. First, rather than one base station (BS), you need dozens or hundreds, deployed across a city. You need automatic and robust mobility management (handoff) to allow users to cross cell lines and continue a phone call. Both of these are actually enabled by semiconductor technology advancement, which made the base stations and the automated wired PSTN cheaper [4].

Frequency reuse and handoff are topics for upcoming lectures.

1.3 Key Terms

Communication between two parties (a “link”), in general, can be one of the following:

- *Simplex*: Data/Voice is transferred in only one direction (*e.g.*, paging). Not even an acknowledgement of receipt is returned.
- *Half Duplex*: Data/Voice is transferred in one direction at a time. One can't talk and listen at the same time. One channel is required.
- *Full Duplex*: Data/Voice can be transferred in both directions between two parties at the same time. This requires two channels.

In a cellular system, there is full duplex communication, between a base station and a mobile. The two directions are called either uplink (from mobile to base station) or downlink (from BS to mobile). The downlink channel is synonymous with "forward channel"; the uplink channel is synonymous with the "reverse channel".

Simultaneous communication on the many channels needed for many users (radios) to communicate with a base station can be accomplished by one (or a combination) of the following *multiple access* methods.

- *Frequency division multiple access (FDMA)*: Each channel occupies a different band of the frequency spectrum. Each signal can be upconverted to a frequency band by multiplying it by a sinusoid at the center frequency of that band, and then filtering out any out-of-band content (see ECE 3500).
- *Time division multiple access (TDMA)*: Every period of time can be divided into short segments, and each channel can be carried only during its segment. This requires each device to be synchronized to have the same time clock.
- *Code division multiple access (CDMA)*: Many channels occupies the same frequency band, at the same time. However, each channel occupies a different "code channel". Like sinusoids at different frequencies are orthogonal (non-interfering), sets of code signals can also be made so that all code signals are orthogonal to each other. One user's channel is multiplied by one code in the set, and at the receiver, can be separated from the other signals by filtering (like frequency bands can be filtered to remove out-of-band content).

In cellular systems, there are actually two types of channels: (1) Control, and (2) Communication. The control channel is needed to tell the mobile device what to do, or for the mobile to tell the BS or mobile switching center (MSC) what to do. The communication channel is the "voice channel" or data channel, the actual information that the user / system needs to convey in order to operate. There are control and communication channels for both forward and reverse directions of the link.

Quite a bit of work goes into planning for frequency reuse. We have two goals. First, a radio should be in range of at least one BS; so BSes must have a certain density so to cover all of an area. Next, a radio must avoid *co-channel interference* from other BSes using the same channel, which means that base stations using the same channel should be widely separated. These are conflicting goals! The first section of this course will teach you how to engineer a cellular system that works to a desired specification.

2 Power and Path Loss

2.1 Transmit Power Limits

A cell is the area in which a mobile is served by a single BS. What is the power transmitted by the radios in a cell system? Limits differ by country.

1. Base station maximum = 100 W maximum Effective Radiated Power (ERP), or up to 500 W in rural areas [5]

2. Cell phone maximum: typically 0.5 W; but limited by power absorbed by human tissue in test measurements (of specific absorption rate).

Cell phone exposure limits are typically set to meet strictest of US / European / other standards.

2.2 Decibel units

We work with values that vary from transmit powers of 500 W to receive powers of 10^{-14} W. Decibel units provide a means to express the wide scale in a manageable way. Further, the vast majority of the time, we will be using the multiplication operation on powers. Engineers find it easier to add than to multiply. When calculating dB power, we add (or subtract) dB values in order to express the resulting power after it has been multiplied (or divided).

Convert from linear power P in Watts to dBW power using:

$$[P]_{\text{dBW}} = 10 \log_{10} P$$

Convert from linear power P in mW to dBW power using:

$$[P]_{\text{dBm}} = 10 \log_{10} P$$

In general, there is an assumed reference P_{ref} which can be used to convert from linear power P to dBP_{ref} using:

$$[P]_{\text{dBref}} = 10 \log_{10} \frac{P}{P_{ref}}$$

Convert back from dB(m/W) power with:

$$P = 10^{P_{dB(m/W)}/10}$$

After converting from dBW, P has units W, and after converting from dBm, P has units dBm.

There are several benefits of dB units:

- Multiplying a linear power by 2 always adds ≈3 dB to the dB power
- Multiplying a linear power by 10 always adds ≈10 dB to the dB power
- Multiplying a linear power by 1.25 always adds ≈1 dB to the dB power

Dividing by one of these constants means subtracting the appropriate dB amount.

- Multiplying P by a constant a adds $[a]_{\text{dB}}$ to the dB power

We can find the result of multiplying / dividing by any sequence of constants by adding / subtracting. For example: multiplying a linear power by 20 adds 13 dB to the dB power. Multiplying a linear power by 0.2 adds -7 dB to the dB power.

Question: What are transmit power limits in dBW? In dBm?

2.3 Large-scale Path Loss

We will discuss fading in detail in subsequent lectures. As a short summary, received power varies quickly over fractions of a wavelength of movement. Even the time-average of the received power, which is less variable than the received power itself, is not purely decreasing as distance between TX and RX (*path length*) increases. However, broadly speaking, if we could average out many measurements of received signal power over many links with path length d, we would see a received power P_r (in mW) that decayed proportional to $1/d^n$, where n is called the path loss exponent. Proportionality gives us $P_r = c/d^n$ for some constant c. If we choose $c = P_0 d_0^n$, then

$$P_r = (P_0 d_0^n) \frac{1}{d^n} = P_0 \left(\frac{d_0}{d}\right)^n = P_0 \left(\frac{d}{d_0}\right)^{-n}$$

for *reference power* P_0 and *reference distance* d_0. In this form, P_0 is the average power at a reference distance d_0. Typically d_0 is taken to be something small, like 1 meter or 10 meters. Converting to power in dBm,

$$\underbrace{10\log_{10} P_r}_{P_r(\text{dBm})} = \underbrace{10\log_{10} P_0}_{P_0(\text{dBm})} - \underbrace{10n\log_{10}\frac{d}{d_0}}_{\text{dB Path Loss}}$$

Question: How much does your average received power change when you double your path length?

Sidenote: How can you read your phone's received power in dBm? There are "field test modes" that differ by phone. For Nokia (I'm told) and iPhones, dial the number *3001#12345#* which puts you into field test mode. On my iPhone 3GS, this would put the dBm received power in the upper left corner of the screen.

References

[1] N. Chandran and M. C. Valenti. Three generations of cellular wireless systems. *IEEE Spectrum*, pages 32–35, Jan/Feb 2001.

[2] G. Fors. The mobile telephone: in Bell System service, 1946-1985. Retrieved Jan. 11, 2010 from `http://www.wb6nvh.com/Carphone.htm`.

[3] A. Goldsmith. *Wireless communications*. Cambridge University Press, 2005.

[4] J. Treichler. A panoramic view of personal wireless systems from 1946 through 2016. In *2009 Virginia Tech Symposium on Wireless Personal Communications*, June 2009. (keynote presentation).

[5] US Federal Communications Commission. Radio frequency safety: Information on human exposure to radiofrequency fields from cellular and PCS radio transmitters. Retrieved Jan. 14, 2010 from `http://www.fcc.gov/oet/rfsafety/cellpcs.html`.