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

Lecture 2

Today: (1) Channel Reuse

- Reading: Today – Mol 17.6, Tue – Mol 17.2.2.
- HW 1 due noon Thu. Jan 15. Turn in on canvas or in the ECE locker labeled "ECE 5325".

1 Channel Reuse

The key idea of cellular communications is that one channel (for example, a FDMA frequency channel) used in one area (cell) can be reused in many different non-neighboring areas (co-channel cells). To be able to reuse a channel, we will need to ensure that the signal power from the desired source (*e.g.*, base station) in one cell is much stronger than the interfering signals transmitted in co-channel cells.

1.1 Signal to Interference Ratio

In particular, *What is the ratio of signal power to interference power?* This is the critical question regarding the limits on how often in space one channel can be reused. This ratio is abbreviated S/I. Signal power is the desired signal, from the base station which is serving the mobile in the same cell. The interference power is the sum of the powers of signals sent by co-channel base stations, which is not intended to be heard by mobiles in the first cell. The S/I ratio is defined as:

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i} \tag{1}$$

where I_i is the power received by the mobile from a co-channel BS, of which there are i_0, and S is the power received by the mobile from the serving BS. NOTE: All powers in the S/I equation above are *LINEAR* power units (Watts or milliWatts), not dBm.

We can generally determine the average interference power using the path loss exponent model, that received power is proportional to $1/d^n$. If this holds for both S and all co-channel interferers I_i, then (1) really depends solely on the distance between the base station and the mobile, and the distances between the co-channel base stations and the mobile.

1.2 Cellular Geometry

What shape is a cell? See Figure 1. These are in order from most to least accurate:

1. A shape dependent on the environment. This would be measured, or computed by simulation. For example, Molisch Figure 17.10.

2. Circular (theoretical): If path loss was a strictly decreasing function of distance, say, $1/d^n$, where d is the distance from BS to mobile, the terrain is flat, and n is the "path loss exponent", then the cell will be a perfect circle. This is never really true, but is often used to get a general idea.

3. An approximation to the theoretical shape: required for a tessellation (non-overlapping repetitive placement of a shape that achieves full coverage. Think floor tiles.) Possible "tile" shapes include triangles, squares, hexagons. Hexagons are closest to reality.

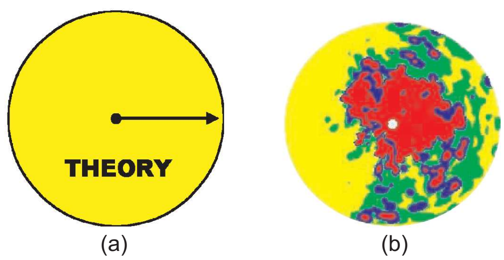

Figure 1: Theoretical coverage area, and measured coverage area. In (b), from measurements, with red, blue, green, and yellow indicating signal strength, in decreasing order. From Newport et. al. [2].

While real-world cellular coverage areas are determined by computer simulation and measurements, it is useful to consider the approximate case because it provides some intuition for the cellular concept. Please don't take these formulas as the way systems are laid out – instead, remember the fundamentals and *how* we do analysis in the approximate case.

1.2.1 Channel Groups

A cellular system assigns subsets, "channel groups", of the total set of channels to each cell. Definitions:

1. U: The total number of unique channels available (based on the total spectrum available)

2. k: The number of channels used in a single cell

3. N: How many different channel groups there are, or "cluster size"

If k is the same in all cells, $U = kN$. (In reality, k may vary between groups.) The first N cells, or "cluster", will "use up" all of the available channel groups. Then, subsequent cells must reuse the same channel groups. We want cells that reuse group A, for example, to be as far apart as possible.

The total number of (non-unique / reused) channels in a deployment area are S times the number of clusters in our deployment area. If we're limited by spectrum (number of channels) and want to increase the capacity over a fixed area, we want to maximize the number of clusters, or minimize the area covered by any particular cluster. This is why we might use smaller and smaller cell diameters as we want to increase our system capacity. *What is the radius R of a cell?* (From C. Furse) *Macrocell*: $R > 2000$ feet, up to 25 miles; *Microcell*: $200 < R < 1000$ feet; *Picocell*: $R \approx 100$ feet; *Femptocell*: $R < 30$ feet.

1.2.2 Cell Arrangement

How are channel groups assigned to particular cells? This can be seen as a graph coloring problem, and is typically covered in a graph theory course. For hexagons, we have simple channel group assignment. Consider $N =$ 3, 4, 7, or 12 as seen in Figure 2. A tessellation of these channel groupings would be a "cut and paste" tiling of the figure. The tiling of the $N = 4$ example is shown in Figure 3.

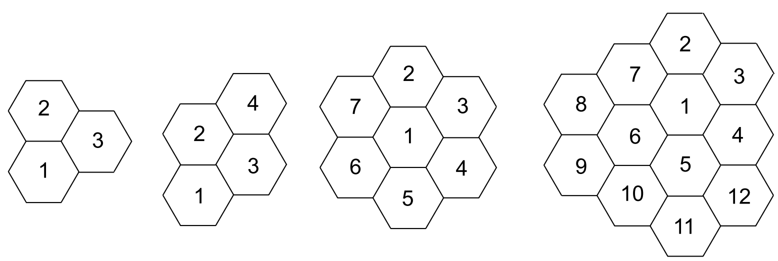

Figure 2: Hexagonal tessellation and channel groupings for $N = 3$, 4, 7, and 12.

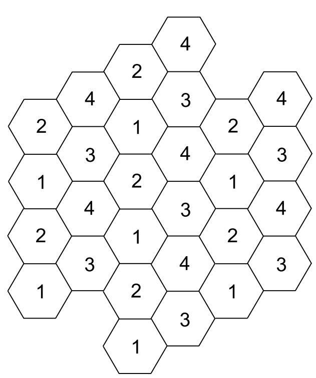

Figure 3: Frequency reuse for $N = 4$.

Example: Call capacity of $N = 4$ system
Assume that 50 MHz is available for forward channels, and you will deploy GSM. Each channel is 200 kHz, but using TDMA, 8 simultaneous calls can be made on each channel. How large is k? How many forward calls can be made simultaneously for the cellular system depicted in Figure 3?

Why wouldn't you choose N as low as possible? Too low N will lead to short distances to the interfering co-channel BSes, and thus high I_i in (1). The signal from the desired base station should be significantly stronger than the signal from a different base station using the same channel (a co-channel base station).

Definitions of two distances that are important to determine the amount of co-channel interference:

- D: The distance between two (first-tier) co-channel base-stations
- R: The distance between a base station and a mobile at the furthest corner of its cell

Note that if a hexagon cell has BS-corner distance R, then the distance from the BS to the center of one side is $R \cos 60^o = R\sqrt{3}/2$.

In a hexagonal tesselation, you can pick which cell will use the same channel group, *i.e.*, be a first-tier co-channel base station. Pick two non-negative integers i and k. The integer i is the number of cells to move from one cell in one direction. Then, turn 60 degrees counter-clockwise and move k cells in the new direction. For Figure 3, this is $i = 2$, $k = 0$. Because of the 60 degree turn, it makes the math more complicated when finding the distance between the centers of these two BSes. The center-of-a-side to opposite center-of-a-side "diameter" for a hexagon is $\sqrt{3}R$. Thus:

$$
\begin{aligned}
D &= \sqrt{3}R\sqrt{(i + k\cos 60^o)^2 + (k \sin 60^o)^2} = \sqrt{3}R\sqrt{(i + k/2)^2 + (k\sqrt{3}/2)^2} \\
&= \sqrt{3}R\sqrt{i^2 + ik + \frac{1}{4}k^2 + \frac{3}{4}k^2} = \sqrt{3}R\sqrt{i^2 + ik + k^2} \qquad (2)
\end{aligned}
$$

The number of cells in a cluster can be shown to be:

$$N = i^2 + ik + k^2$$

Thus combining with (2),

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

The ratio of $D/R = \sqrt{3N}$ is called Q, the co-channel reuse ratio.

Note this is only true for hexagonal cells, not in general.

1.3 SIR in Hexagonal Plan

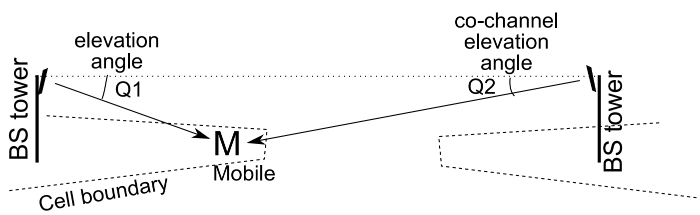

Figure 4: Desired, and interfering signal for a mobile (M) from a serving and co-channel base station.

We typically look at the worst case, when the S/I is the lowest. This happens when the mobile is at the vertex of the hexagonal cell, *i.e.*, at the radius R from the serving BS. So we know $S = cR^{-n}$. What are the distances to the neighboring cells from the mobile at the vertex? This requires some trigonometry work. The easiest approximations are (1) that only the first "tier" of co-channel BSes matter; (2) all mobile-to-co-channel-BS distances are approximately equal to D, the distance between the two co-channel BSes. In this case,

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i} \approx \frac{cR^{-n}}{i_0(cD^{-n})} = \frac{(D/R)^n}{i_0} = \frac{(3N)^{n/2}}{i_0} \quad (3)$$

where i_0 is the number of co-channel cells in the first tier. For all N, we have $i_0 = 6$ (try it out!); this will change when using sector antennas, so it is useful to leave i_0 as a variable in the denominator. Typically S/I requirements are reported in dB.

Example: AMPS design

Assume that 18 dB of S/I is required for acceptable system operation. What minimum N is required? Test for $n = 3$ and $n = 4$.

1.3.1 Downtilt

The Molisch book covers antenna downtilt briefly in 9.3.3. Compare the elevation angles from the BS to mobile (Q1 in Figure 4) and co-channel BS to the mobile (Q2 in Figure 4). Note Q2 is lower (closer to the horizon) than from the serving BS. Downtilt is the idea of providing less gain at angle Q2 than at Q1, by pointing the antenna main lobe downwards. If the gain at Q1 is X dB more than the gain at Q2, we add X dB to the S/I ratio. This narrow vertical beam is pointed downwards, typically in the range of 5-10 degrees. The effect is to decrease received power more quickly as distance increases; effectively increasing n. This is shown in Figure 5.

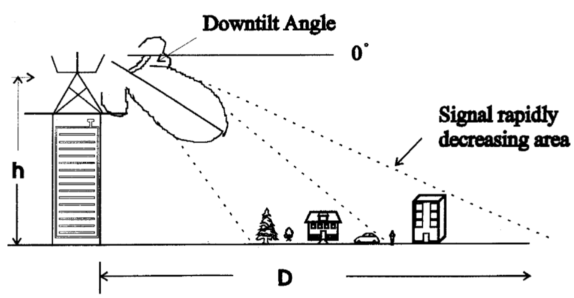

Figure 5: A diagram of a BS antenna employing downtilt to effectively increase the path loss at large distances. From [1].

Ever wonder why base station antennas are tall and narrow? *The length of an antenna in any dimension is inversely proportional to the beamwidth in that dimension.* The vertical beamwidth needs to be low (5-10 degrees), so the antenna height is tall. The horizontal pattern beamwidths are typically wide (120 degrees or more) so the antenna does not need to be very wide.

References

[1] W. Jianhui and Y. Dongfeng. Antenna downtilt performance in urban environments. In *IEEE Military Communications Conference, 1996. MILCOM'96, Conference Proceedings*, volume 3, 1996.

[2] C. Newport, D. Kotz, Y. Yuan, R. S. Gray, J. Liu, and C. Elliott. Experimental evaluation of wireless simulation assumptions. *SIMULATION: Transactions of The Society for Modeling and Simulation International*, 83(9):643–661, September 2007.