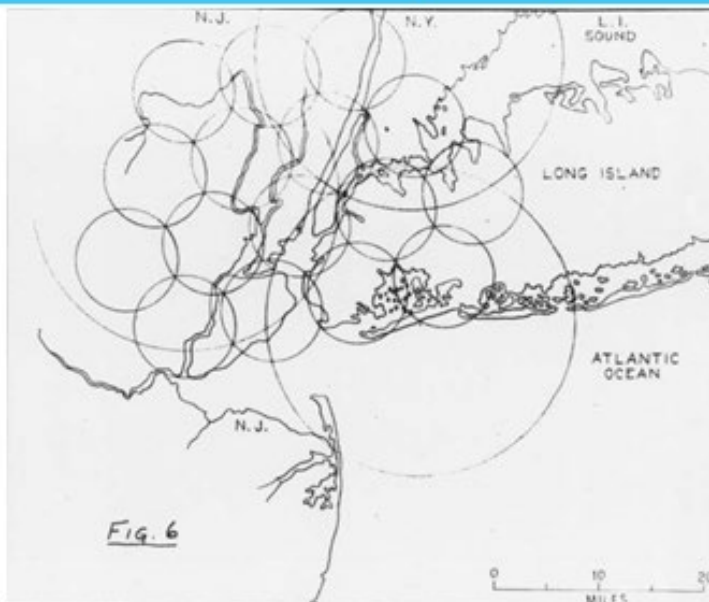


## Lecture 4- Pre-lecture reading

### Channel reuse: the technology of cellular

The earliest proposal for what might be called a cellular system was made by Doug Ring, a Bell Labs engineer, in 1947. His goal was not to create huge capacity, as was the idea in later proposals. His goal was to achieve continuous coverage everywhere in the US. He observed that the systems being installed were centered on cities and towns, and due to the limited number of channels there were gaps between such coverage areas with no service, and service could be poor as one approached the boundaries of the existing systems. He proposed creating a continuous grid of coverage areas (what today would be called cells) so there would be good-quality service anywhere in the US. The overlapping circles of coverage he shows were later drawn as hexagons. The hexagons depict the actual coverage of the individual cells, and are neater to draw. His cells were not particularly small (5-15 miles in radius) and his system did not increase system capacity. Moreover, neither the channels nor the computer and switching technologies that the system would require were available in 1947. It was a futuristic idea well before its time and received little attention.

#### Doug Ring's "cells" in the New York area (1947)



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A decade later, when the FCC was considering what to do with the spectrum between 500 MHz and 1 GHz, AT&T suggested that a system with grid of smaller cells could achieve greater capacity, but the idea was new and had not been studied extensively. As discussed in the previous lecture, the FCC gave all the spectrum to TV broadcasters (for cultural and educational programming), and Bell Labs moved on to other ideas like Picture Phone and fiber optic transmission and computer controlled switching systems.

More time passed. The TV broadcasters disappointed the FCC by offering sex and violence instead of Shakespeare, and in 1968 the FCC offered to reassign some of that TV spectrum

to mobile radio, if a more “spectrum-efficient” system could really be built. Fortuitously (or perhaps because they were expecting FCC action) Bell Labs had begun some studies of a small cell, high capacity mobile telephone system in 1966, and was happy to respond with a proposal. In 1971 a detailed cellular proposal was submitted to the FCC and a large development team was created at Bell Labs. The march toward a cellular system had begun in earnest, but another decade would pass before the cellular system would become a commercial reality.

The key to AT&T’s proposal was that it would make much more efficient use of the channels than had been possible with previous technology, by using small coverage areas that could “reuse” each channel many times in the same city. Instead of putting a high-powered transmitter in the center of a large city, AT&T proposed to distribute low power transmitters throughout the coverage area, creating those small coverage areas we are calling cells. A channel that was used in one of these small cells could be re-used for a different call only a few cells away (for example, in all the red cells on slide 7). Some minimum separation was required between cells that re-used the same channels to prevent interference. This re-use distance turned out to be 4.6 cell-radii (as shown in the figure), which allowed seven channels (or seven groups of channels) to serve all the cells in a big system, as shown on the slide.

## Small coverage areas allow each “set” of channels to be re-used many times

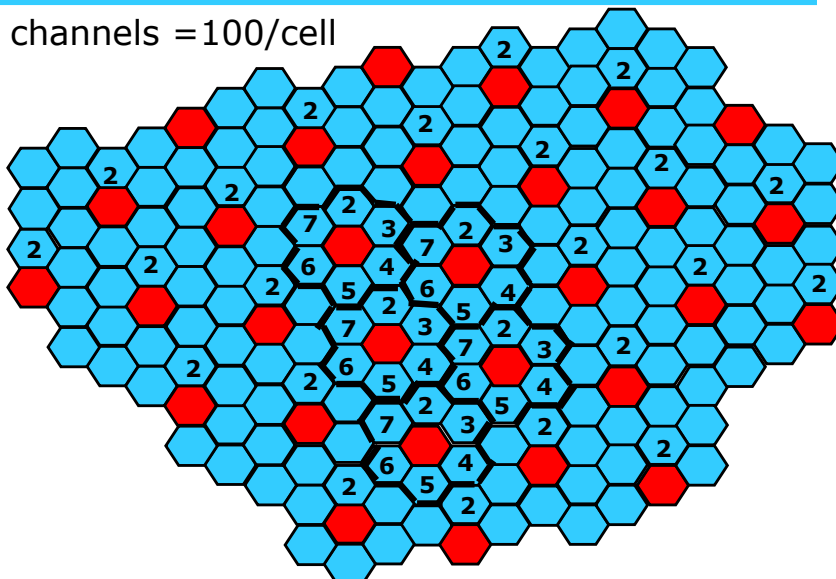


Nearby cells couldn’t use those “red” channels, so at least a few sets of channels would be needed. The more distance you needed between “co-channel” cells (cells with the same channels) the more “channel-sets” (different groups of channels) you would need to create and (for reasons we will discuss) the more expensive the system became. Years of experiment and design went into studying radio interference in different terrain (urban and

rural; hilly and flat) before it was decided to use a separation of 4.6 times the cell radius. This required 7 sets of channels, as shown below, using the hexagonal grid characteristic of cellular drawings. If we had 700 channels, we could put 100 in every cell, no matter how many cells there are. It doesn't matter how big the system is, as Doug Ring suggested. It could cover the whole country.

For this separation (4.6 times the cell radius)  
we need 7 channel-sets to fill all the cells

700 channels = 100/cell



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This relationship, in which a channel can be re-used 4.6 cell-radii away, is independent of the size of the cell. When we use smaller cells, the interference is closer and stronger, but the radio signal we want to receive is closer and stronger as well, so the ratio of signal power to interference power (and thus the quality of the call) remains the same. [This relationship was approximately true even for the old systems, which used a coverage radius of about 20 miles and a separation between systems of about 100 miles.] In the proposed cellular systems, however, the individual cells were much smaller than the coverage area of the system, so each channel could be used many times in the same system, for different calls. If the cells were small enough, each channel might be used 100 times in the same system. It was possible to imagine systems with hundreds of thousands of users, using cells with radii as small as 1 mile.

Today we have systems with millions of users, with cells as small as  $\frac{1}{4}$  mile in radius, but such capacities were beyond even the dreams of the early cellular engineers. A few hundred thousand users in a system with 1 mile cells seemed impressive enough (and difficult enough). The engineers who worked on that first system were imagining 2M users in 20 years. The reality was 200M users talking 8x as much. From pre-cellular systems to the dawn of smartphone "data" a decade ago, the number of subscribers to cellular service in the US has increased by a factor of 6000x (from 50 thousand to 300 million) and they are talking 8 times as much. This 48,000x increase in voice capacity is based in part on added spectrum and in part on improvements in radios, but the biggest factor from the beginning to

today is the use of smaller and smaller cells (more and more channel- reuse, so every channel gets used more and more times). The original idea of cellular reuse is alive and well in the 3G/4G world.

We will see in the next lecture that “cell-splitting” (the constant addition of new base stations to create smaller cells and more reuse) is expensive. Doubling the capacity of a cellular system with a given number of channels meant doubling the number of base stations, and as we will see in the next lecture that means doubling the cost of the system. As long as doubling that capacity was because there were twice as many paying customers, everything was OK (the cost per user remained manageable). We will discuss the relationship between system cost and monthly charges and profit in lecture 6 (understanding costs and profits is essential to strategy). Later in the course we will discover the huge problem caused by the smartphone revolution in the last 10 years. The capacity of the systems has had to increase 50x for video and all those new apps. Cell-splitting (adding base stations) to achieve that new level of capacity for smart phones would have been too expensive, so other methods had to be found. We will explore how that was done in Lecture 16, but we have a lot of ground to cover first.

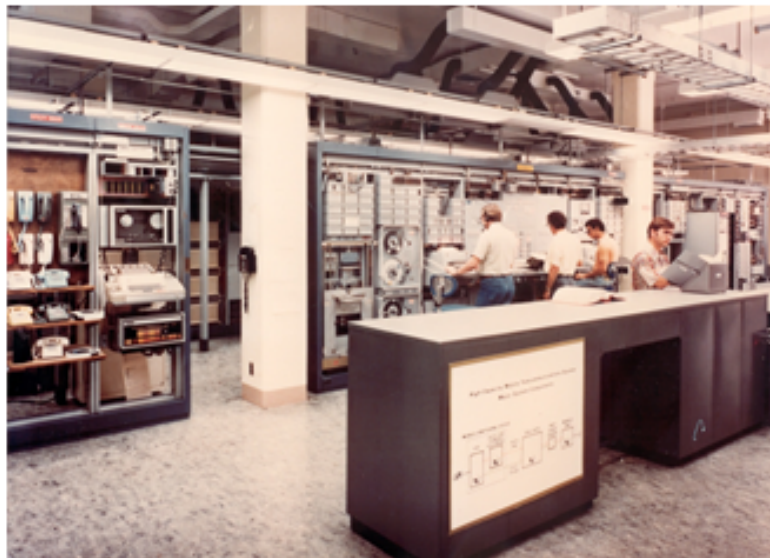
There were enough technology problems in cellular to make it endlessly fascinating for Bell Labs engineers. There was almost no data on propagation for the new frequencies. How far could you transmit a signal? How well did it fill in behind hills, or penetrate buildings? Then there was a lot of information that had to pass between the system and the cell phone—system identification, telephone numbers, channel assignments—much more information than had been used in any system of the time. Instead of a few tones to identify idle channels and send digits, there would have to be high-speed data transmission along with voice. The mobile unit had to be located and the call would have to be switched to a new radio, in a new cell, on a new channel when the car changed cells. This had to be done in milliseconds with high reliability and no noticeable clicks.

And we needed “handoff” if the mobile changes cells  
(switching to a new base station and changing channels)



More importantly, there was a lot of computation needed to control functions like call setup and handoff, at a time when AT&T's new Electronic Switching Systems (ESS) were just coming into use. They were controlled by powerful computers and provided a platform upon which programmers could add the new cellular logic without having to design a whole new controller. Minicomputers were used in every base station and the first microprocessors would make cell phones smarter than had ever been possible before. The central switch, base stations and cell phones became a distributed control system that was a new concept at the time.

Massive computers at the central switch  
and Minicomputers at the base stations  
and Microprocessors in the mobile  
and millions of lines of code



The Mobile Telephone Switching Office (MTSO) in Chicago

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The earlier proposals for cellular would not have been possible with the technology that was available at the time, but by the 1970s, the necessary technology was falling into place. Cellular was as much the child of computer technology as of radio technology, and the required investment for thousands of base stations cells would be very large. These factors gave AT&T a big advantage over competing service providers like the RCCs or system providers like Motorola. AT&T had the technology to design the system and the wealth to build a nationwide cellular network so its arguments for a new AT&T monopoly were powerful, but those arguments also ensured that the Department of Justice and companies like Motorola would oppose the cellular proposal strenuously.

In Lecture 5, we will see that the unusual economics of the cellular system supported the argument that a monopoly was justified. Motorola and the DOJ were not persuaded.