Random Access. Cellular System Design. Multiuser Detection. Area Spectral Efficiency

Lecture Outline

- **Random Access**
- **Cellular System Design**
- **Multiuser Detection**
- **Area Spectral Efficiency**

1. **Random Access**

   - Multiple access requires a dedicated controller and control channel to assign channels. This entails system overhead.
   - Dedicated channel assignment can be inefficient for short and/or infrequent data transmission.
   - In random access there is no dedicated channel assigned to each user. Rather users access the channel randomly whenever they have data to send.
   - The most common forms of random access are Aloha and Random Aloha (*this is not covered on exams or HW*). In both cases, the data is packetized with a certain packet length/time duration. In Pure Aloha, a packet is sent whenever available. A collision occurs if more than one user sends packets that overlap over any fractional packet duration at the receiver. Packets received in error are retransmitted after a random delay. In slotted Aloha, packets are only sent during pre-defined timeslots. A collision occurs when packets overlap but there is no partial overlap of packets. Packets received in error are retransmitted after a random delay. For L the rate of new and backlogged packets, assuming Poisson arrivals, throughput under Pure Aloha is $T = Le^{-2L}$ and under Slotted Aloha is $T = Le^{-L}$

2. **Cellular System Design**

   - Basic premise: Frequency channels, timeslots, or codes are reused at spatially sparate locations.
   - Exploits power falloff with distance so that interfering users result in SINR that is above the desired target.
   - The SINR in a cellular system depends on base station locations, user locations, propagation conditions, and interference reduction techniques.
   - Efficiency maximized by minimizing reuse distance - system is interference limited.
   - Base stations perform centralized control functions.

3. **Multiuser Detection**

- In CD systems with semi-orthogonal codes and in TD/FD/CD cellular systems, users interfere with each other.
- Interference is generally treated as noise, so systems required to meet a particular performance target become interference-limited (or SINR limited). Often uses complex mechanisms to minimize impact of interference (power control, smart antennas, etc.)
- Interference can be mitigated by Multiuser Detection (MUD, which exploits the fact that the structure of the interference is known and hence some/all of the interference can be removed.
- MUD structures generally trade performance for complexity.
- The optimal MUD is a maximum-likelihood detector which simultaneously detects all users. For N users, ML MUD is exponentially complex in N.
- A common detector used in practice is successive interference cancellation, which sequentially subtracts out the strongest interferer. This technique is optimal from a Shannon capacity perspective, but in practice it suffers from error propagation.
- MUD is not used much in practice due to the added complexity of the signal processing and the requirements for a high dynamic range/precision in the A/D converters such that the weak user signals are not discarded by the A/D.

4. **Area Spectral Efficiency (ASE)**

- Define *reuse distance* R_D to be the minimum distance between any two base stations that use the same code, frequency, or time slot.
- Since these resources are reused at the distance R_D, the area covered by each resource is roughly the area of a circle with radius $.5R_D$: $\pi(.5R_D)^2$.
- For N users per cell, a reuse distance R_D, and a total bandwidth allocation B, the multicell system capacity is defined as the multiuser rate region per Hertz divided by the coverage area reserved for the cell resources:

$$C_{\text{multicell}} = \frac{(R_1, R_2, \ldots, R_N)/B}{\pi(.5R_D)^2},$$

  where $(R_1, R_2, \ldots, R_N)$ is the set of maximum rates that can be maintained by all users in the cell simultaneously.
- The area spectral efficiency of a cell is defined as the total bit rate/Hz/unit area that is supported by a cell's resources. Thus, the area efficiency is

$$A_e = \frac{\sum_{i=1}^{N} R_i/B}{\pi(.5R_D)^2}.$$

  The rate R_i is just the capacity of the ith user in the cell, which depends on $\gamma_i = S_i/I_i$, the received signal-to-interference power of that user, and B_i, the bandwidth allocated to that user. We could also define R_i to be the maximum possible rate for the ith user under a given set of system parameters.
- If γ_i is constant, then $R_i = C_i = B_i \log(1 + S_i/I_i)$.

- Typically, γ_i is not constant, since both the interference and signal power of the ith user will vary with propagation conditions and mobile locations. When γ_i varies with time, R_i equals the time-varying channel capacity of the ith user:

  $$R_i = B_i \int \log(1+\gamma_i)p(\gamma_i)d\gamma_i.$$

  It can also be defined as the maximum possible rate for the ith user under the given system parameters and time-varying channel conditions.
- In general, it is extremely difficult to obtain the distribution $p(\gamma_i)$ in a multicell system, since this distribution depends on the power control policy and channel variations of both the signal and the interferers.
- Simplified analysis and Monte Carlo simulations indicate that ASE increases exponentially as cell size shrinks. Hence, future cellular systems will be hierarchical, with small cells for capacity (and energy efficiency) and large cells for coverage.

Main Points

- Random access more efficient than multiple access for short/infrequent data transmission
- Cellular systems reuse channels to maximize efficiency - systems become interference limited. Interference reduction increases capacity. MIMO trades diversity-multiplexing-interference reduction.
- Multiuser detection mitigates interference through joint or successive detection
- Area spectral efficiency captures system capacity as a function of cell size and reuse distance. This efficiency grows exponentially as cell size shrinks. Small cells and reuse one typical of next-gen cellular.