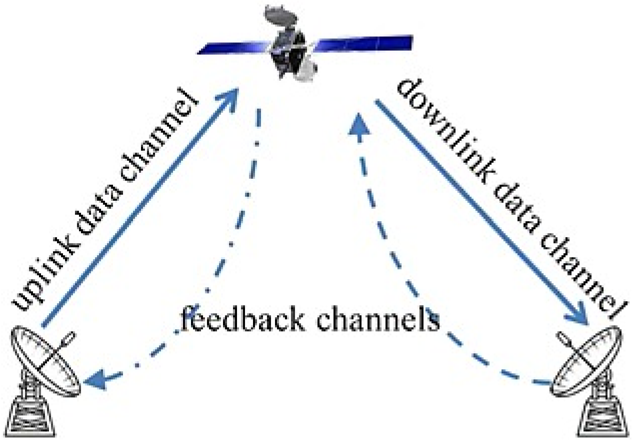
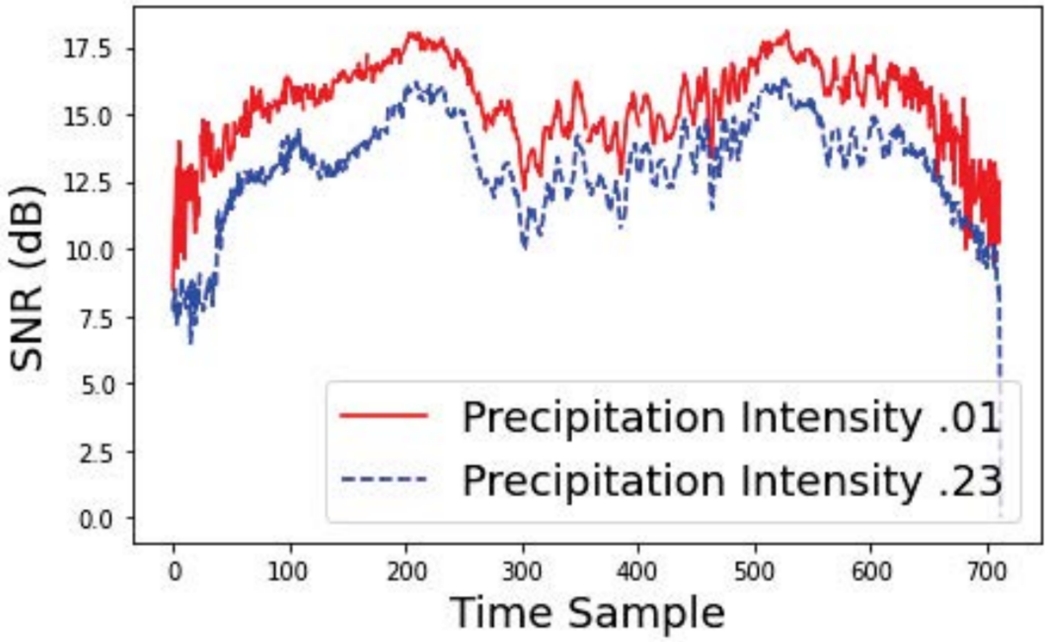
Satellite Networks, Nov 10

- Satellites are a unique device since they are always moving in a predictable orbit
    - There are three main orbits: **GEO**, **MEO**, and **LEO**
    - GEO is **geosynchronous** orbit, which is unique in that a satellite can orbit around the earth such that it remains above one point on the earth's surface (GIF: https://en.m.wikipedia.org/wiki/File:Geosynchronous_no_geostationary_orbit.gif << The figure-8 that is formed by the projection of the orbit onto earth is very small so it can be assumed to be a single point above the earth)
    - MEO is **medium-earth orbit** (2000km - 36000km), and it contains the **GPS constellation** along with the other navigational constellations from other countries (like Galileo)
    - LEO is **low-earth orbit** (below 2000km), which is one of the lowest orbits and is becoming the most popular space to fly communication satellites. This lecture focused on LEO in particular, since it is a hot topic nowadays. LEO is especially suited for communications with earth, since it is close to earth, reducing latency
- The state-of-the-art communication architecture for satellite-ground communications is the **bent-pipe architecture**
    - It is called a bent-pipe because the satellite acts as a relay between two locations on the ground



    - Unfortunately, this produces a bottleneck in uplink from ground stations near highly populated areas, like cities
    - Satellites can communicate with each other through inter-satellite links. **Optical/laser links** are popular

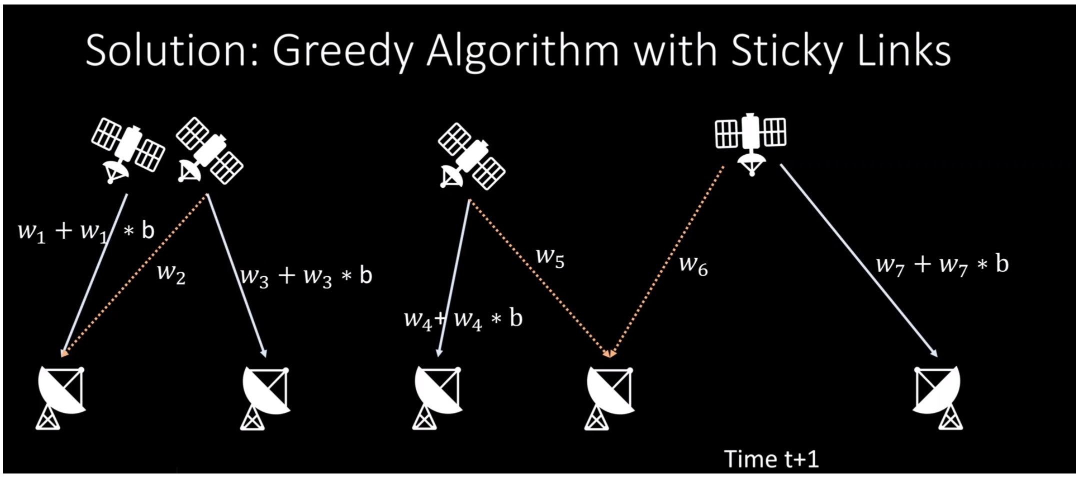
- Because satellites move in a predictable orbit and weather can be predicted (up to a point), it is possible to predict the SNR of a channel between a ground transmitter and a satellite receiver:



  - The SNR of the channel is lowest as the satellite is close to the horizon. This is because the satellite is further from the ground receiver
  - In the X-band (8-12GHz), a common band for satellite comms, signals are attenuated by weather
  - (The reason why this graph dips while the satellite is directly overhead is because the receiver antenna hardware was faulty. Normally this would not happen)
- **Medium access is a problem** in satellite networks
  - Some concepts in WiFi medium access can also be applicable to satellite networks, like the hidden terminals problem. Two devices can be communicating with the same satellite at the same time, but not realize they are transmitting while the other is transmitting
  - **One solution is directional beams** on the satellite to reduce the number of devices that it is communicating with at one time. The downsize to this is that small devices like IoT devices or drone-mounted devices cannot fit an antenna array capable of high-power directional satellite transmissions
  - Recently, cellular companies are pushing for direct satellite-phone communication which would enable phone calls over satellites. Device manufacturers will need to design chips for this special type of communication
- **Challenge 1: Data Downlink**
  1. Ground stations are expensive
  2. Cloudy weather is a problem. If a satellite cannot download its images to a ground station due to poor SNR from weather, it must wait for the next available ground station. This is a big problem for latency-sensitive data, like wildfire images
  3. Low revisit rate is a problem. Mentioned above
- **Solution 1: Distributed Hybrid Ground Stations**

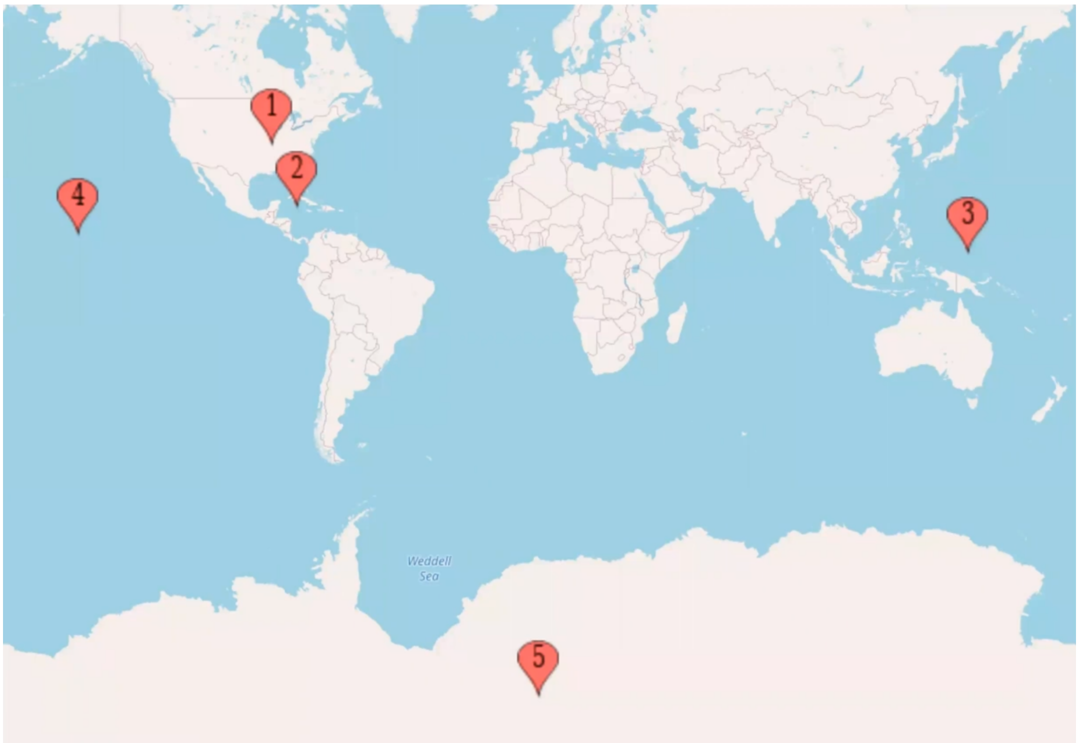
- Distributing stations throughout the globe provides the system with locational diversity. This dampens the negative effects of bad weather in one location
- More receive stations means lower latency for download
- Having more receive stations than transmit stations is better anyways, since obtaining the licensing for transmission can become a year-long process
- **Rate adaptation becomes an issue** when satellites are streaming data down to heterogenous receivers
  - We have already seen Robust Rate Adaptation for 802.11 Wireless Networks, which heavily relies on feedback between device and AP, but what do we do when the device cannot provide the AP with feedback, like in this case?
  - Solution: L2D2 queries a weather model and orbital mechanics to help predict SNR between the satellite and a given ground station over a span of time. Using this prediction, the satellite can vary its transmit bitrate to stay just below the channel's capacity. This is just like a WiFi router reducing its modulation from 256-QAM to 128-QAM because the user is walking away from the AP. (The theoretical capacity of a channel in bps is $C = B\log_2(1 + SNR)$)

- **Challenge 2: Scheduling Satellite-GS Links**
  - It takes time for a ground station to physically move its beam to point at a satellite
- **Solution 2: Modify the Bipartite Matching Problem to Incentivize Sticky Links**
  - As it is normally formulated, the bipartite matching problem focuses on one point in time. Solving the problem allows us to know the best matching between satellites and ground stations at a single point in time. However, this formulation does not consider history- i.e. which ground station was focusing on which satellite in the previous time step. In order to modify the bipartite matching problem, the authors add an additional term to each edge cost that takes into account the cost of switching satellite-GS links



- The authors quantify the efficiency gains of their approach by using two datasets

- 4 expensive ground stations in the US (and Antarctica :))



- Over 100 inexpensive receivers in the SatNOGS network

- **Open questions**
  - How to best implement caching on satellites?
  - What makes edge compute on satellites different from edge compute on earth?
  - How to design ground infrastructure which is capable of uplink? Could this hardware be adopted by IoT devices?
  - How to work around the unique power variations of harvesting solar energy from space?
  - How to track all the objects orbiting the earth? (SSA: Space situational awareness)