Array Signal Processing for Cellular CDMA Mobile Communications

Peter M. Grant

Professor of Electronic Signal Processing

The University of Edinburgh

Scotland

Email: pmg@ee.ed.ac.uk

http://www.ee.ed.ac.uk/~profiles/sas/

Contents

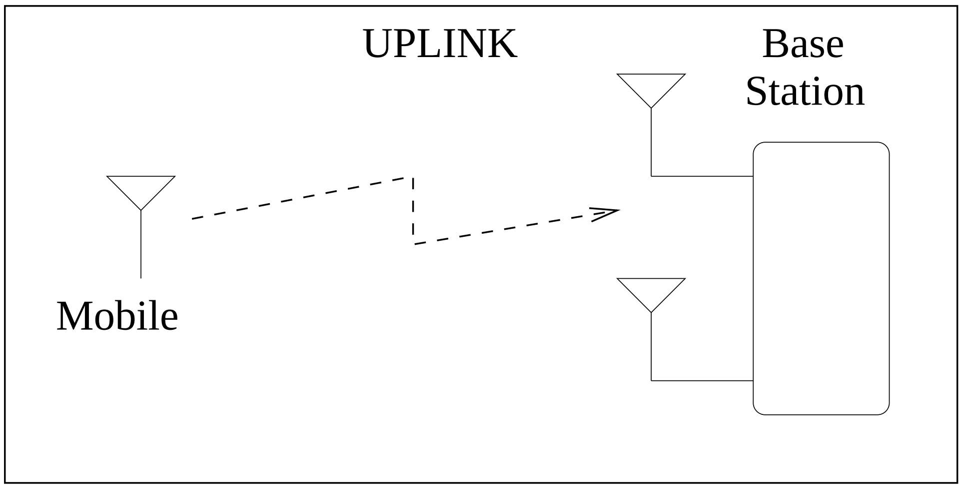
Array Processing

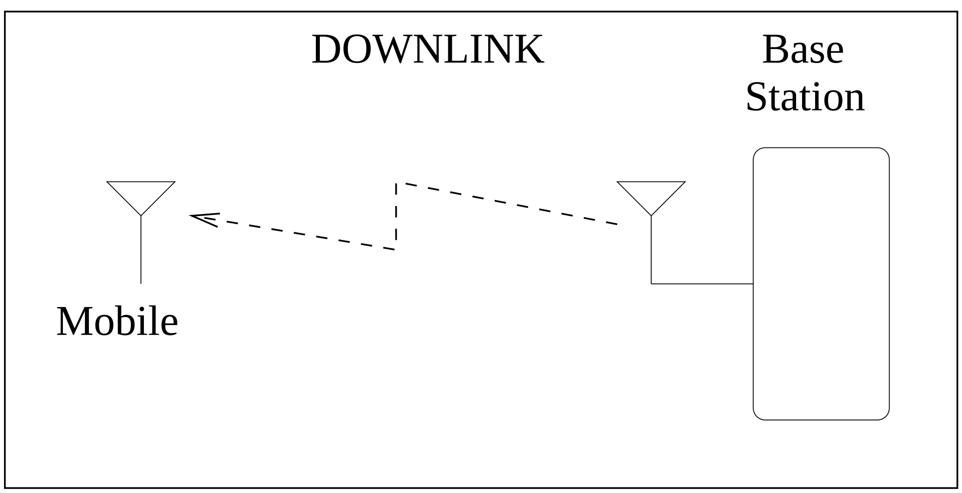
- Null Steering: Widrow 1967
  Applebaum 1976
  Gabriel 1976
  Compton 1979

- Military Applications: Jammer Reduction

- Cellular Systems: Interference Reduction
  J. Winters (Bell Labs) 1980-90s
  A. Paulraj (Stanford University) 1990s

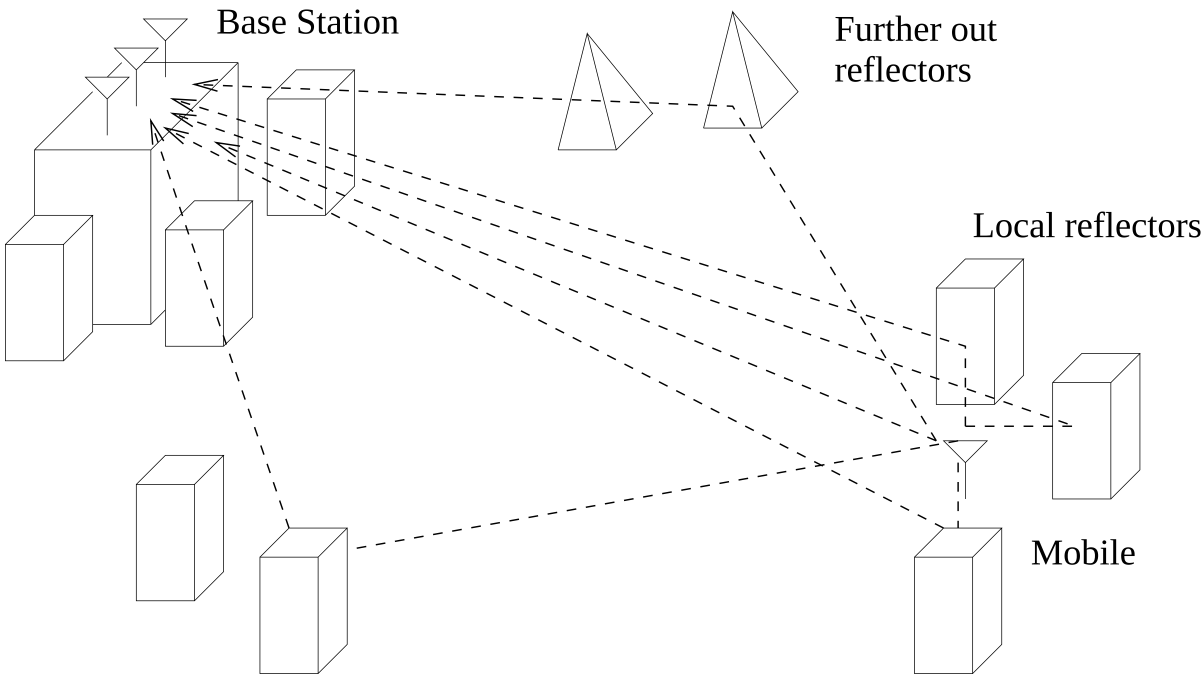
Current Cellular System Design





- Dual diversity is used on *uplink*; single antenna system on *downlink*; typically 120° sectorisation.

Spatial Channel Modelling

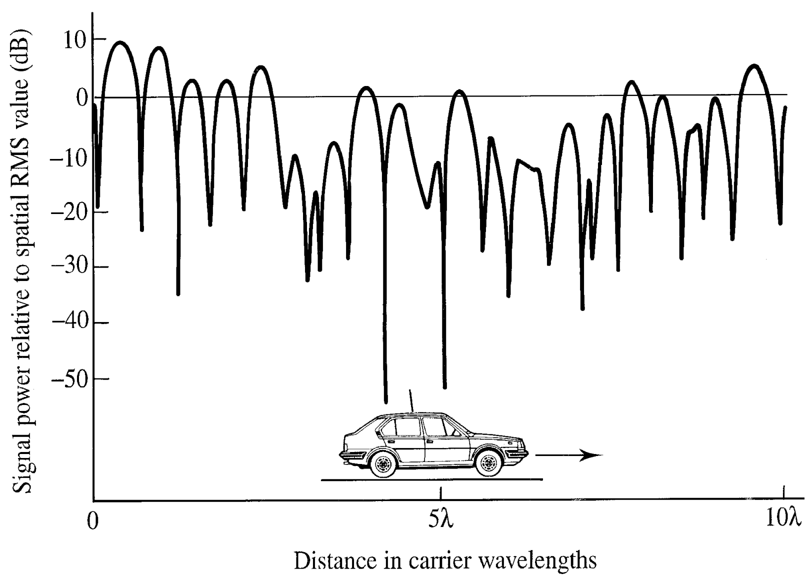


- *Local reflectors at mobile:* nearby buildings cause reflections with small time delays.

- *Further out reflectors:* major obstacles give rise to specular multipath components with large delays and angle spreads.

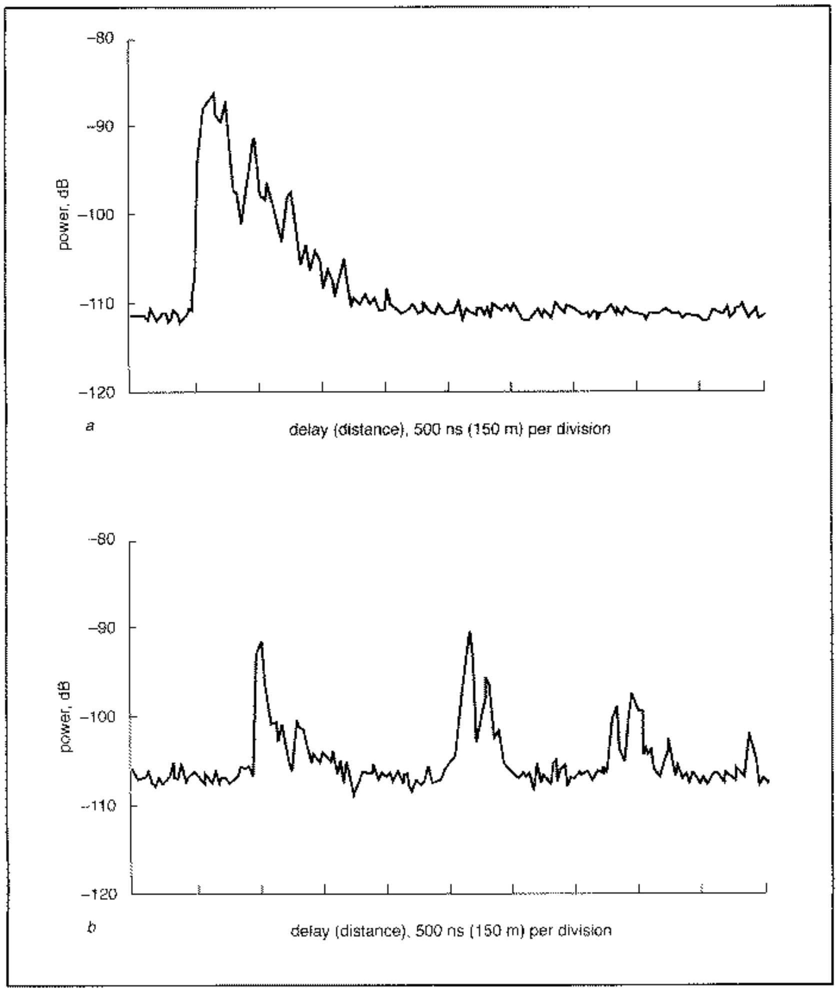
- *Reflectors at base station:* buildings near cell site may give rise to additional reflection/diffraction effects.

Rayleigh Fading



- Received power profile for a moving vehicle in a Rayleigh fading multipath channel.

Multipath Dispersion

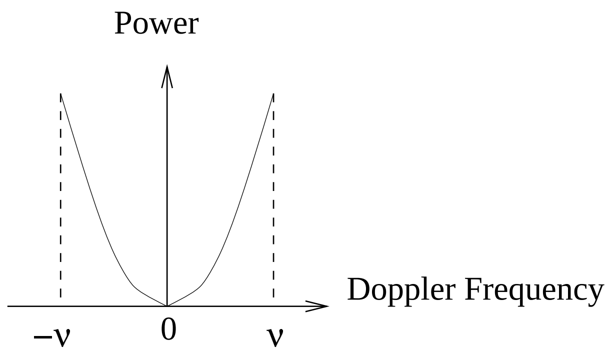


- Power delay profiles for suburban sites in Edinburgh: (a) single component (b) series of components (after Ward).

Other Channel Effects

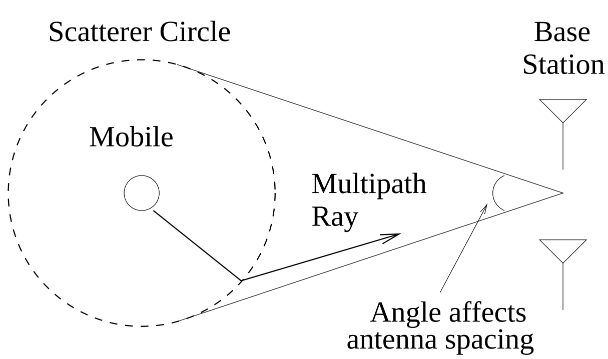
1. Frequency dispersion – due to motion of mobile.

- Classical Doppler model frequency profile for unmodulated carrier:

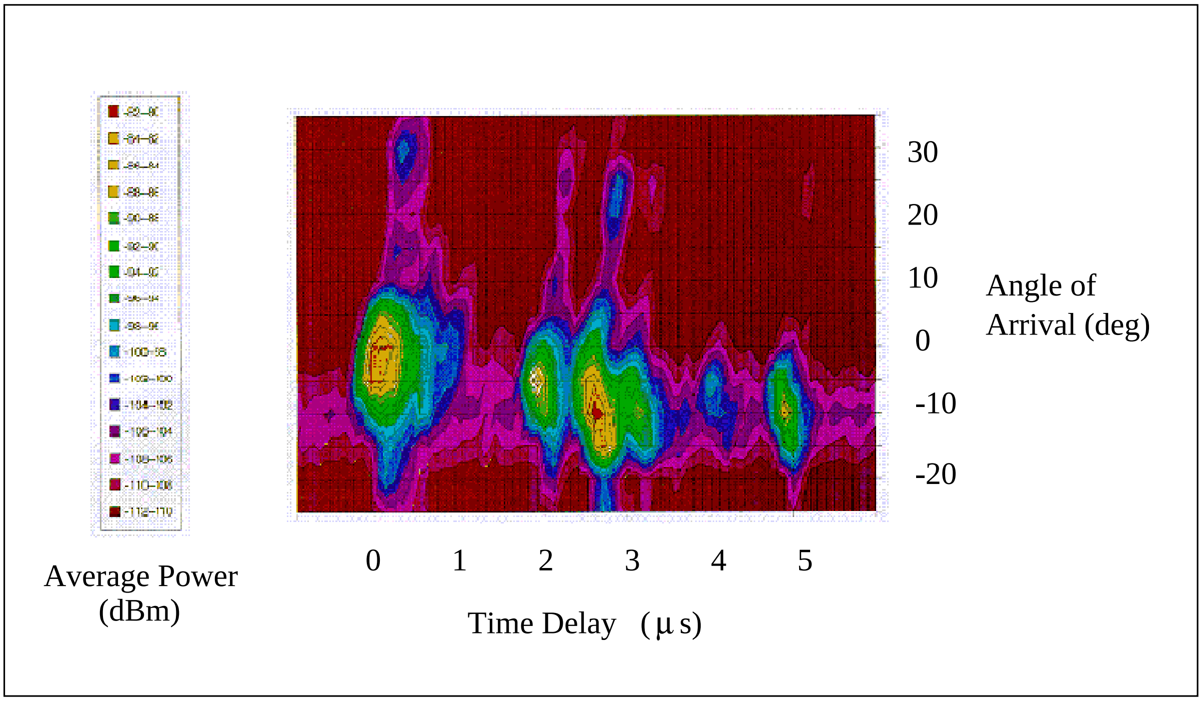


2. Multipath Angular width

- Determines antenna spacing to obtain space diversity



Typical Multipath Channel



- Example scattering map showing received signal power in delay and angle of arrival (after Ward).

Direct-Sequence CDMA

1. All users are accommodated in the same RF frequencies.

2. Each user is identified by a different binary spreading code.

3. Capability to resolve multipath energy.

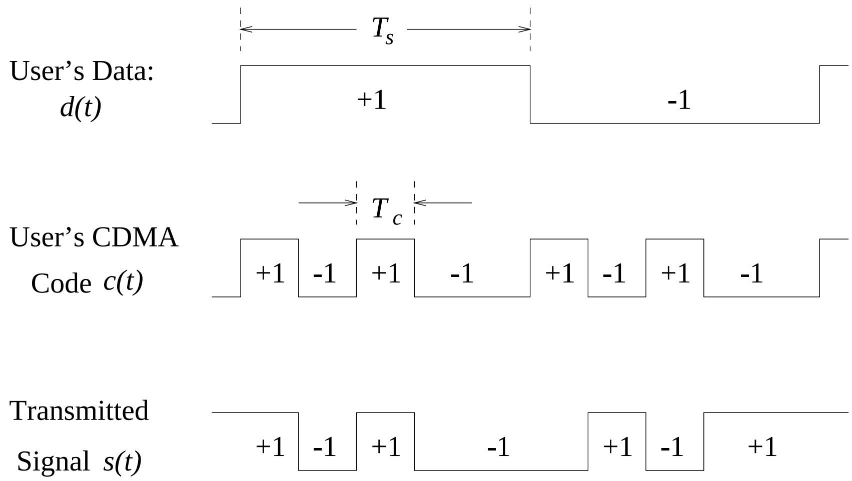
4. Transmissions are asynchronous on the *uplink*, but synchronous on the *downlink*.

5. Power control is needed on the *uplink* to mitigate the near–far problem.

6. Capacity is limited by multiple–access interference from other users.

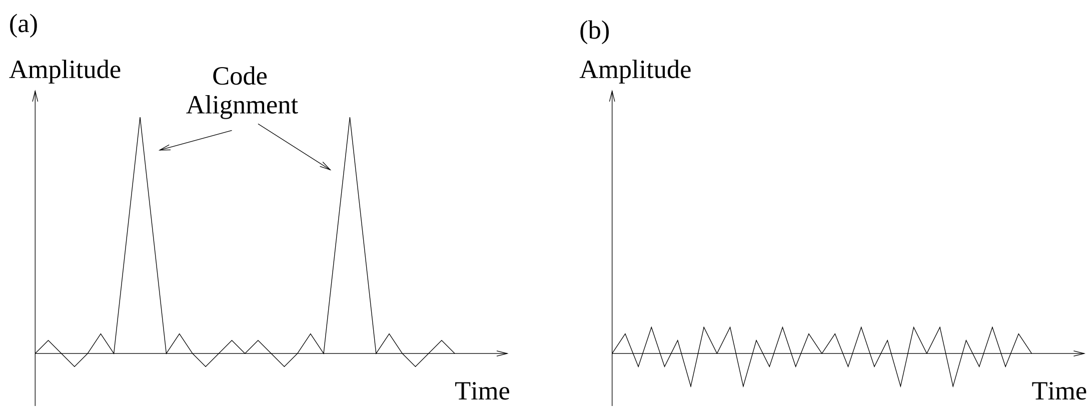
Direct Sequence Modulation

- Bandwidth Spreading:



Processing Gain $W = T_s/T_c$.

- Code Correlation Functions:



(a) Cross–correlation function with data and
(b) Cross-correlation between subscribers.

Obtaining Diversity

Obtain multiple independent copies of transmitted signal to reduce probability of deep fades. Sources of diversity gain:

Multipath Diversity:

- Code correlation function can permit multipath energy to be resolved at different delays.

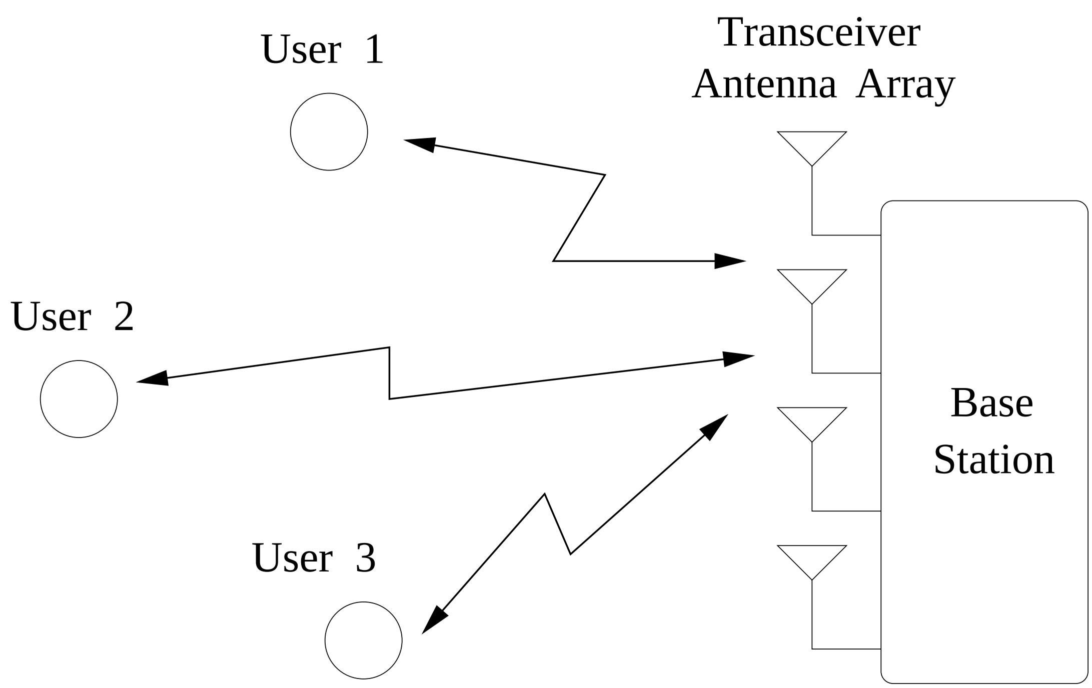
Coding/Interleaving:

- Interleaving codeword bits at the transmitter can exploit Doppler fast fading.

Space Diversity:

- Employ widely spaced antennas to obtain uncorrelated fading.

Antenna Arrays and Diversity



Exploit *diversity gain* and *interference suppression* to:

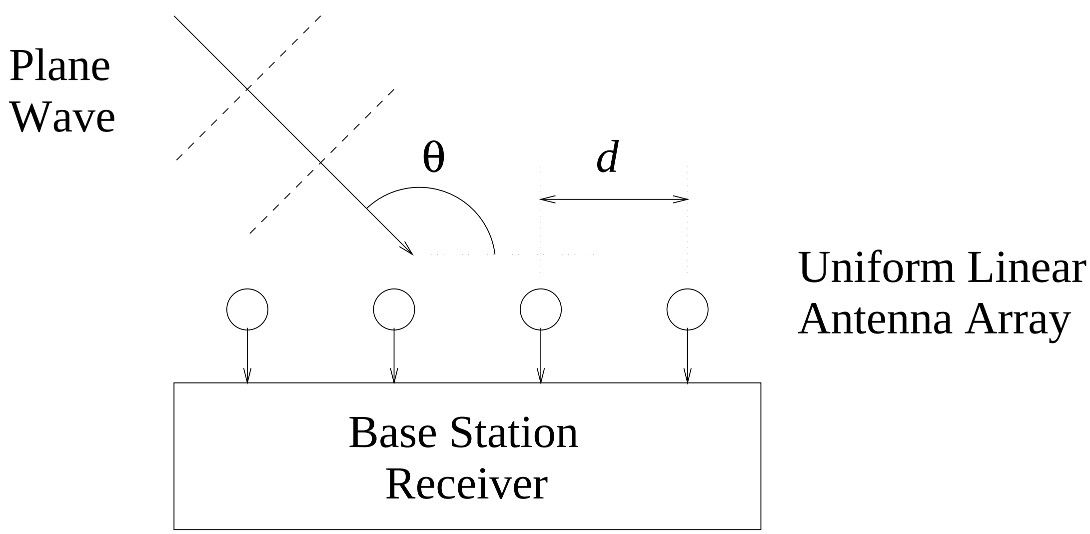
1. Improve system capacity
2. Increase range and coverage of the cell
3. Improve link quality

CDMA Capacity Issues

- Multiple users on same RF bandwidth, different CDMA codes.
- Power control required to prevent near–far effect.
- **Uplink:** Users operate asynchronously – codes cannot be made orthogonal. All users in system cause interference.
- **Downlink:** Same cell users are synchronous – codes can be orthogonal. Other cells cause interference.
- System capacity is limited by other user interference

Antenna Arrays

1. Employ M antenna elements.
2. "Narrowband" model is assumed – time delays modelled as phase shifts.
3. Use uniform linear array (ULA) geometry.

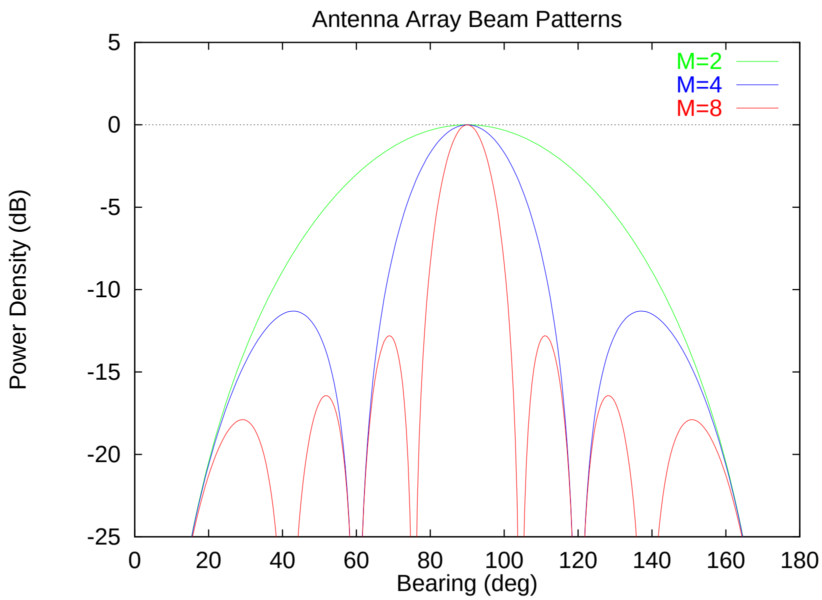


4. The "steering vector" for $d = 0.5\lambda$:

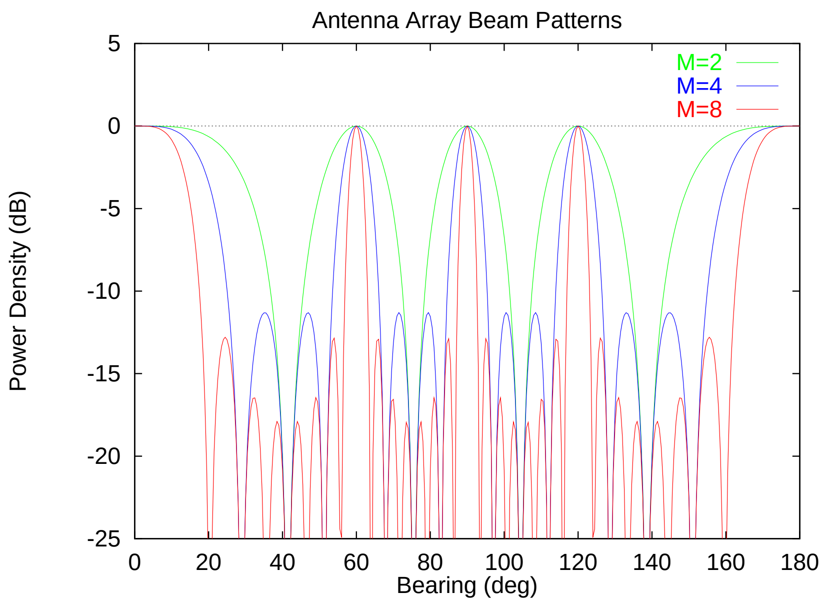
$$a(\theta) = [1, \exp\{j\pi\cos(\theta)\}, \ldots \exp\{j(M-1)\pi\cos(\theta)\}]^T$$

Array Beam Patterns

- Array Spacing $d = 0.5\lambda$:



- Array Spacing $d = 2.0\lambda$:



The Uplink

CDMA uplink channel characteristics:

1. Multipath dispersion in time.
2. Fast fading effects.
3. Angular spread of energy.
4. Multiple access interference.

Base station receiver requirements:

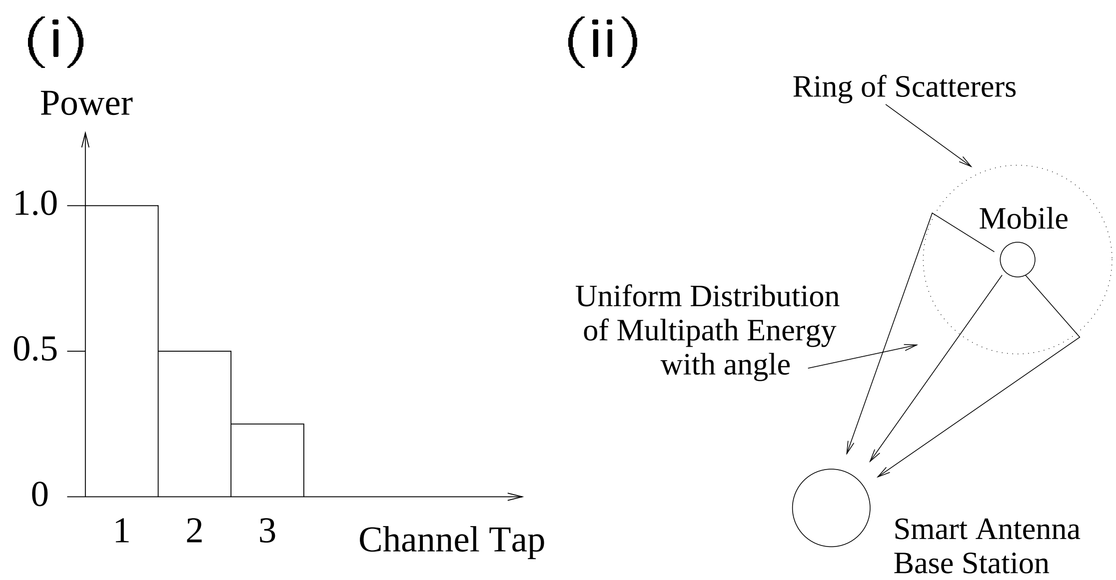
1. Combine signal energy in time and space.
2. Track rapid channel variations.

Uplink Channel Modelling

1. In a urban environment, multipath propagation leads to Rayleigh fading of the signal power over time.

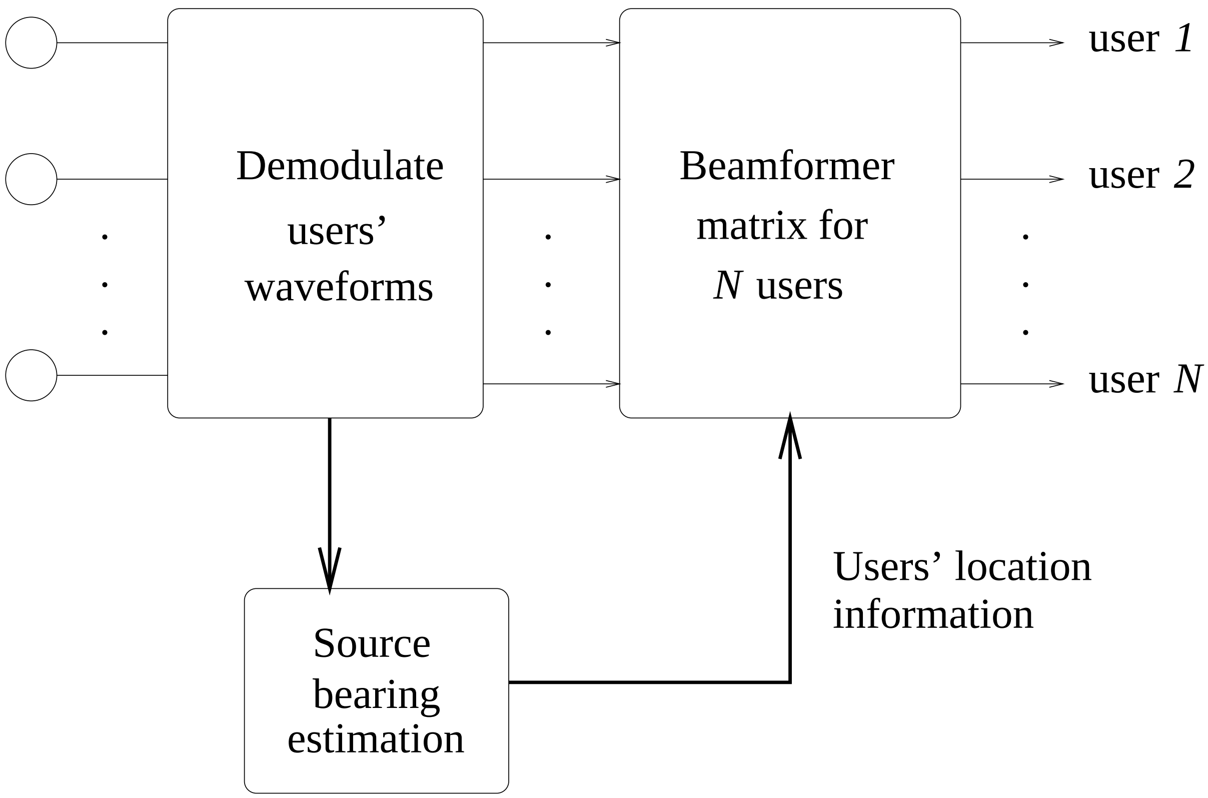
2. If the code chip period $T_c <$ delay spread T_d, can resolve multiple channel taps.

3. Antenna array simulations must model required angle of arrival θ and angular width Δ for each channel tap.



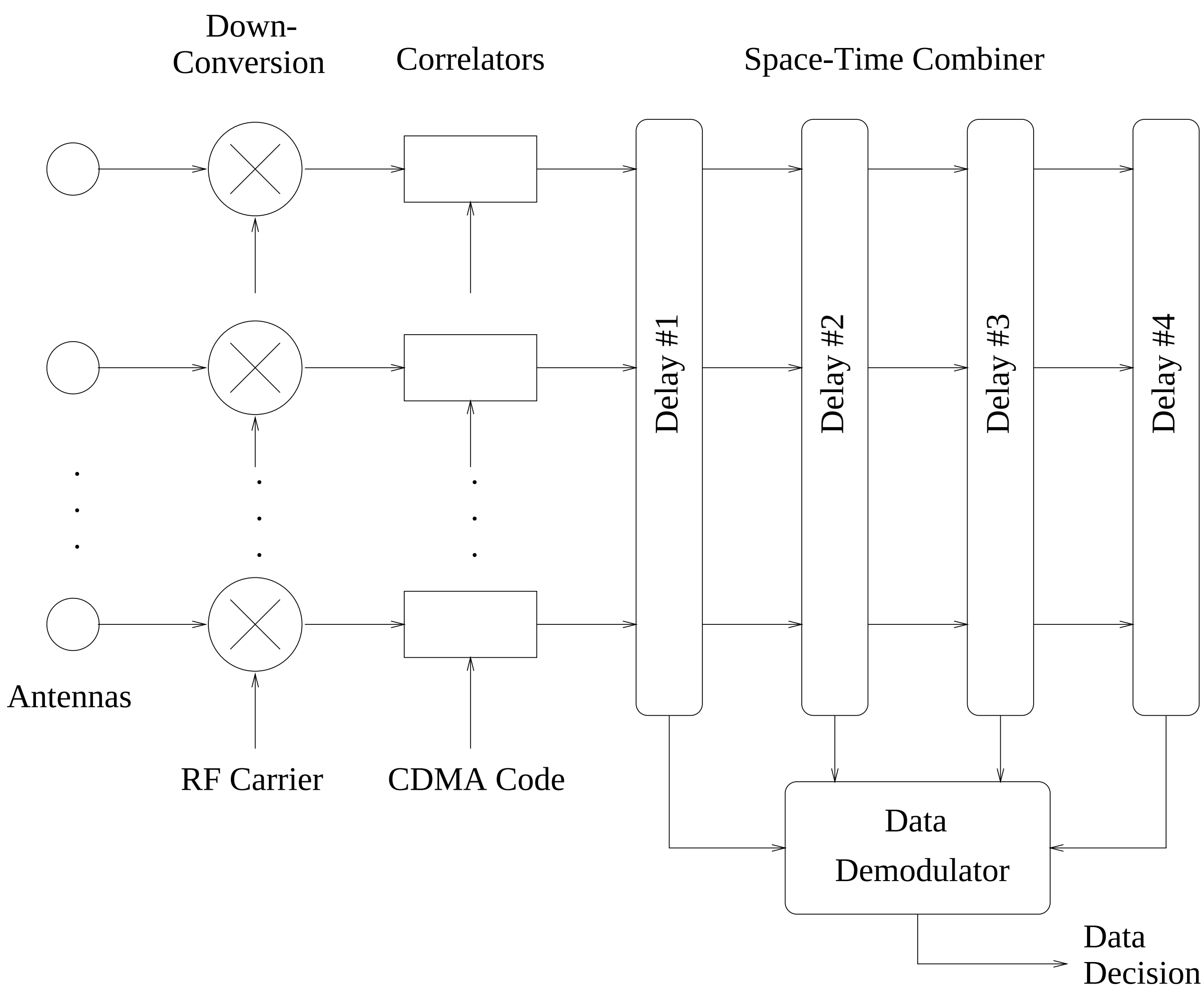
(i) Multipath profile (ii) spatial tap model.

"Smart" Antenna



Uplink CDMA Receiver Structure

- The "Space–Time" combiner:



- The receiver algorithm chooses weights to optimally combine signal energy in space and at different time delays.

User Distribution Effects

1. Perform studies of three scenarios to assess the effect of different user locations in a cell.

2. Each user has the following five multipath tap, Rayleigh fading channel:

$$H(z) = 1 + 0.5z^{-1} + 0.25z^{-2} + 0.125z^{-3} + 0.06225z^{-4}$$

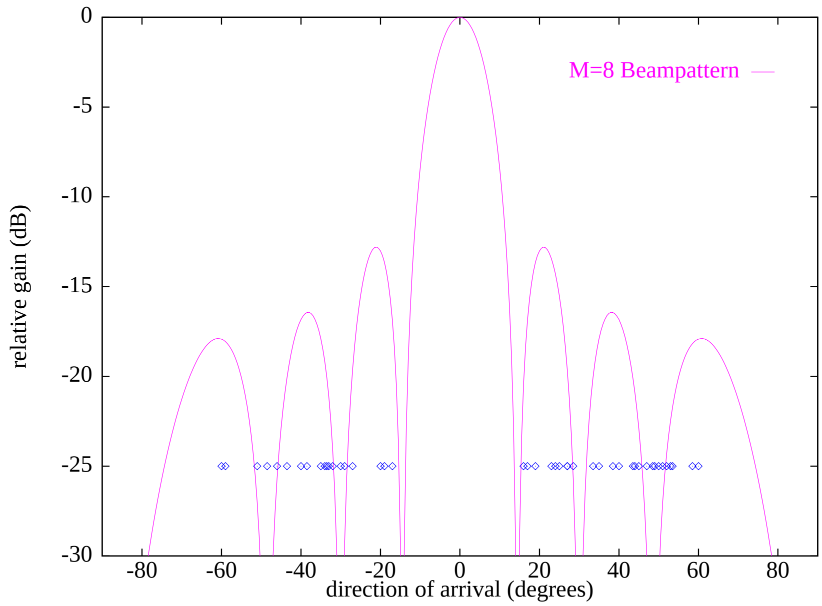
3. The system uses DPSK modulation and has a CDMA processing gain $W = 127$.

4. The locations of all users' multipaths are known perfectly; the 2D-RAKE receiver is used to combine the multipath energy.

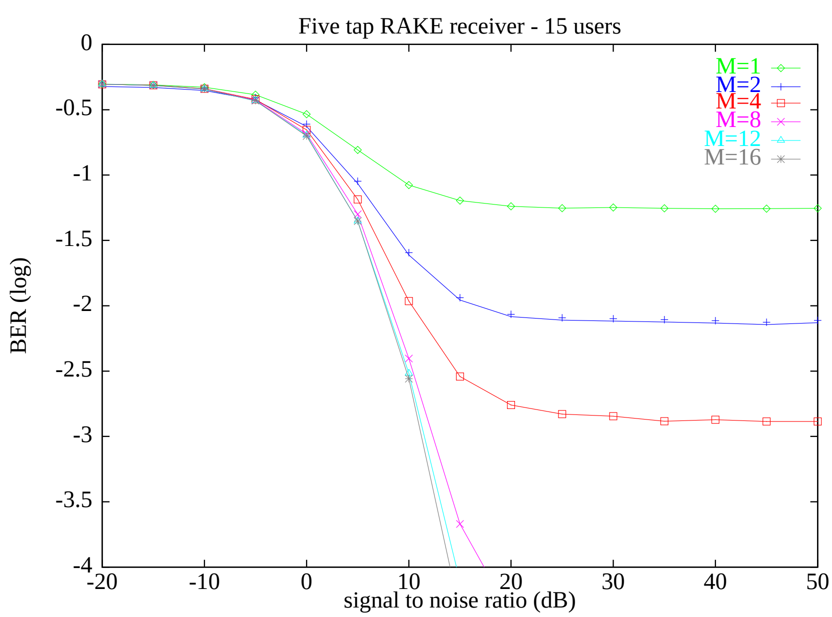
5. Bit error ratio curves calculated for 15 user case, with different array sizes M.

Good User Layout Example

- Layout of user & interferers:

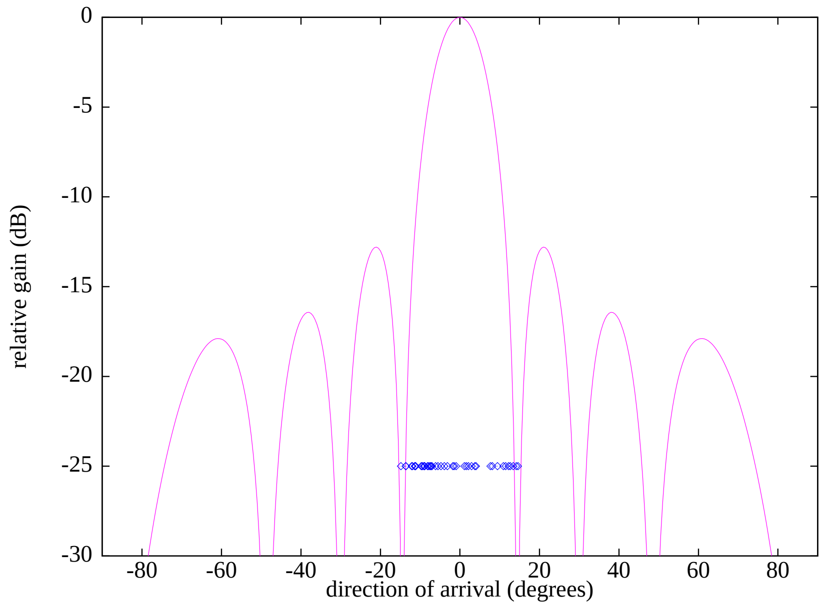


- Resulting bit error ratio curves:

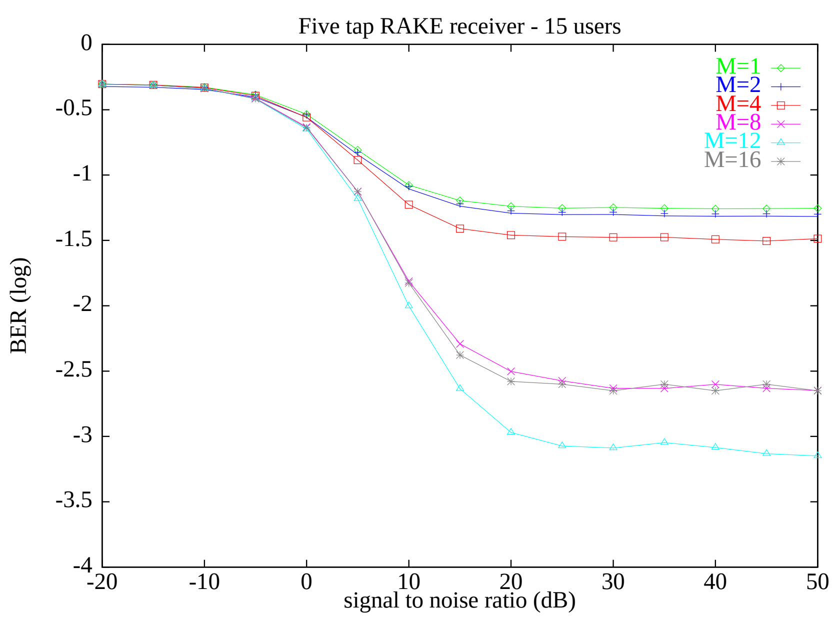


Bad User Layout Example

- Layout of user & interferers:

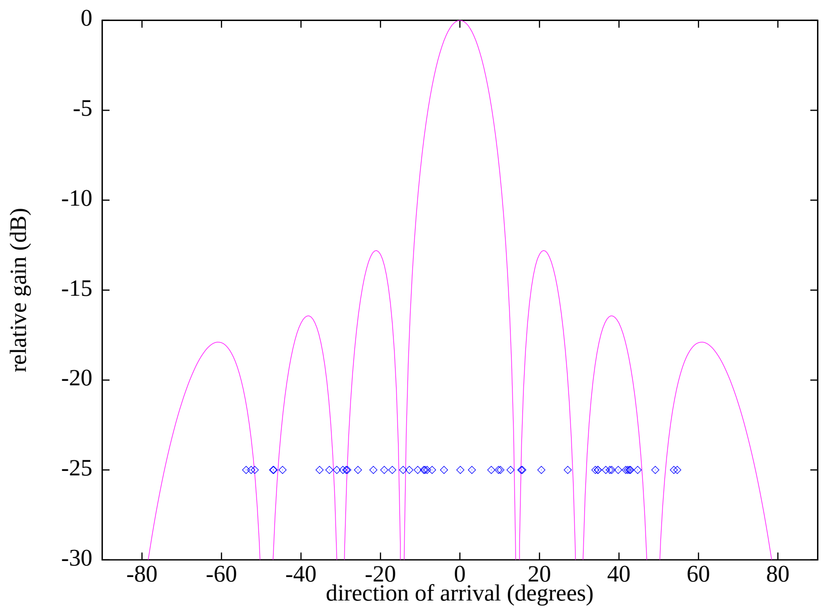


- Resulting bit error ratio curves:

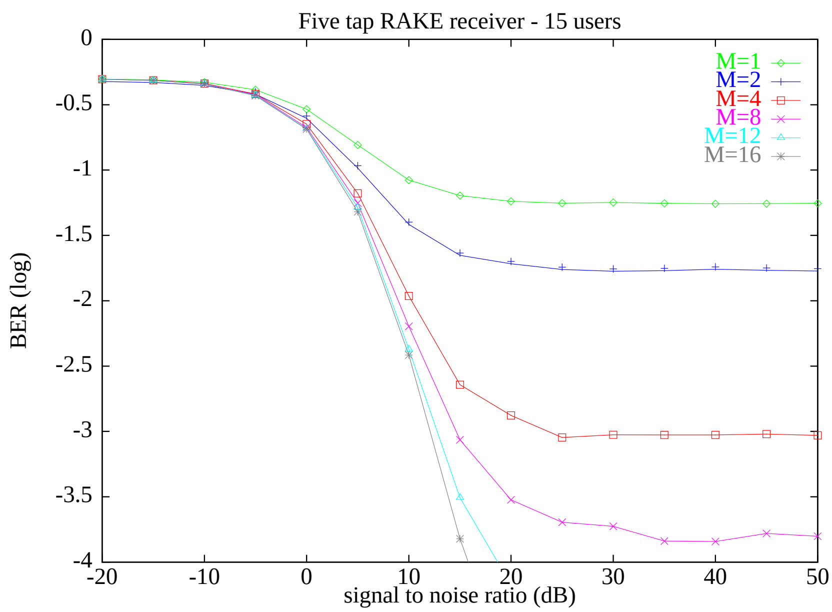


Typical User Layout Example

- Layout of user & interferers:



- Resulting bit error ratio curves:



TDMA Array Processing

- Simultaneous user transmissions in single timeslot
- Conventionally require large geographical separation of cells using same frequencies $\rightarrow$ large channel re–use factor
- M element antenna array can null out up to $M-1$ users per slot, but with reduced diversity gain.
- Such a system can employ a smaller channel re–use factor
- Alternatively can have up to $M-1$ users per slot in one cell $\rightarrow$ Space division multiple access (SDMA).

Antenna Arrays with CDMA

- Exploit *spatial redundancy* to suppress noise and directional co–channel interference.

- In general, number of active users $\gg$ array size M. Cannot normally null–out all interferers.

- Doubling array size should halve the interference and noise level.

- Can also exploit additional space diversity – diminishing returns as order increases.

Receiver Algorithms

- Fixed beam (spatial DFT) receiver
- Direction of arrival (DOA) measurement
- Channel multipath estimation
- Interference suppression techniques

Receiver Algorithms [2]

Fixed Beam: set of fixed beam patterns cover sector.

- Simplest algorithm; “easy” to implement.
- Problems with cusping losses and wide angular spread.

DOA Receiver: measure angles of arrival of multipath channel and steers beams.

- Useful for finding subscriber location.
- Array calibration problems; some algorithms sensitive to coherent multipath.
- Unambiguous array manifold required; diversity gain limited.

Receiver Algorithms [3]

Channel Estimation: estimate amplitude & phase for each multipath component.

- Complexity is reasonable
- Good performance if interference is spatially white

Interference Suppression: apply prewhitening filter before channel estimation.

- High complexity receiver.
- Provides the best performance in most cases.
- Improvement over channel estimation alone may be limited.

Practical Issues

The gains from an antenna array system can be used to:

- Increase system capacity
- Reduce mobile transmit power
- Improve quality of service
- Increase cell range or coverage area

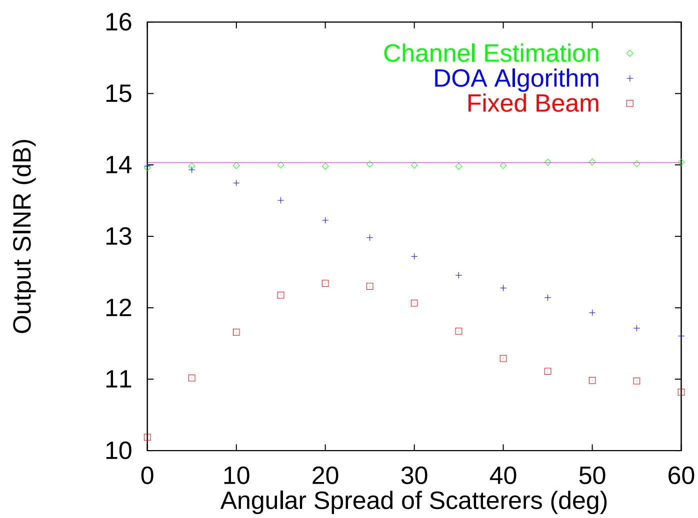
But, there are algorithm issues:

- Complexity and numerical stability
- Speed of convergence
- Operation on fast fading channels

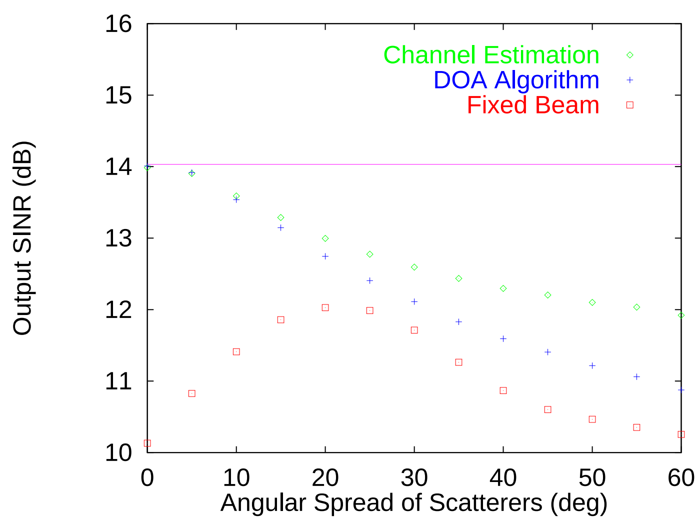
Algorithm Comparison

- 1GHz system; 8 element array spacing 0.5λ; 50 data symbols used for estimation.

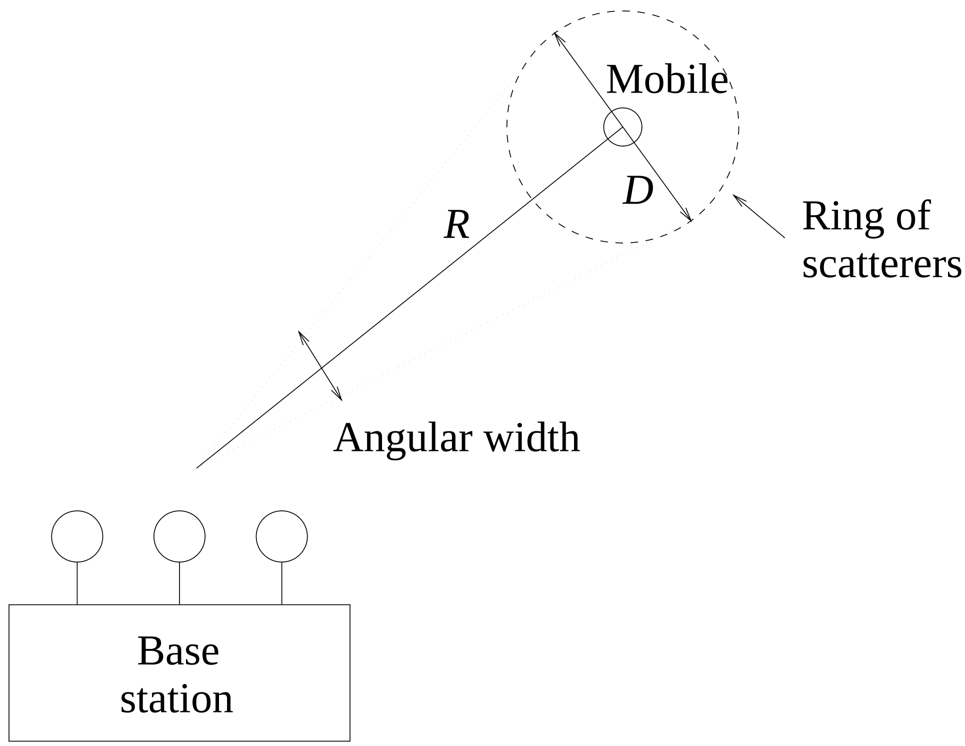
- Results for 0 Hz Doppler:



- Results for 200 Hz Doppler:



Mobile Range



$$\text{Mobile Range} = \frac{R}{D}$$

- Mobiles close to the base station have small range ≈ 1 and thus have large angular width $\approx 50°$.

Uplink Capacity Simulation

1. Four tap Rayleigh fading power profile:

   $H(z) = 1 + 0.5z^{-1} + 0.25z^{-2} + 0.125z^{-3}$

2. Three normalised mobile ranges - 1, 4 and 16 (angular widths $53^o, 14^o$ and 3.5^o).

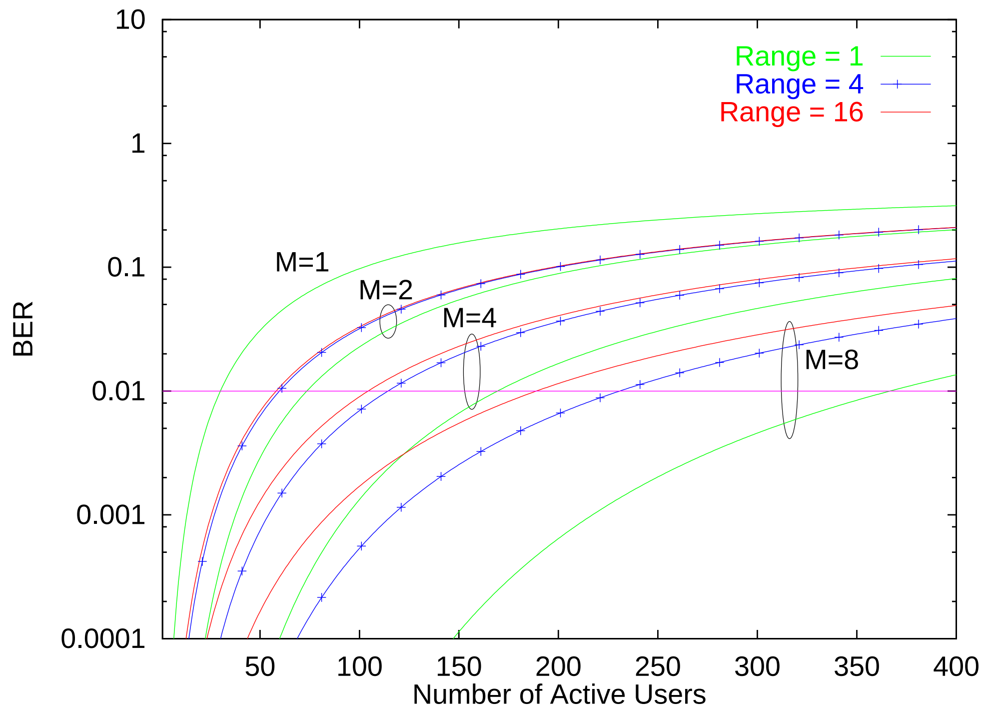
3. CDMA processing gain of $W = 256$; perfect average power control of each user.

4. There are M antenna elements covering a 120^o sector. Users are uniformly distributed in angle.

5. Assume perfect channel estimation – performance estimated at position with lowest beamformer gain.

6. Capacity assessed for a BER of 10^{-2}.

Capacity Results



Plot of BER vs Number of Users for different M and mobile ranges with $W = 256$.

M	Mobile Range		
	1	4	16
1	30	30	30
2	73	59	58
4	169	114	105
8	366	230	189

Maximum number of users for different M and mobile ranges for BER of 10^{-2}.

The Uplink: Discussion

1. Antenna arrays can easily be added to existing CDMA systems, to provide significant capacity gains.

2. The fixed beam suboptimal solution has limited complexity & is easy to install.

3. Antenna array receivers must track "channel variations" well, particularly in low SNR and fast fading environments.

4. Require sophisticated array processing receiver.

5. The system capacity is sensitive to mobile position and available diversity gain.

Downlink Considerations

- Most cellular standards use frequency division duplex (FDD) for the uplink & downlink.

- In an FDD system, the uplink/downlink separation is at least 40 MHz – Rayleigh fading uncorrelated between links.

- The downlink channel cannot be directly measured in current cellular systems.

- Two approaches to downlink – diversity techniques and downlink beamforming.

Downlink Algorithms

- *Diversity Techniques*: Use multiple antennas to induce diversity at the mobile – e.g. soft–handoff.

- *Downlink Beamforming*: There are a number of possible methods here:

1. Use uplink channel estimates to transmit on the downlink.

2. Transmit known beam patterns & use feedback from the mobile to calculate the channel.

3. Employ time division duplex (TDD) techniques, so that the uplink and downlink channels are on the same frequency.

Conclusions

1. Considered the integration of antenna arrays within CDMA cellular systems.

2. Antenna arrays offer large capacity increases on the uplink and the base station added cost is minimal.

3. Precise choice of array processing algorithm is an ongoing research investigation.

4. Providing effective beamforming on the downlink is a more formidable problem.

Acknowledgements

- Colleagues in Signals and Systems group at the University of Edinburgh:
  http://www.ee.ed.ac.uk/~profiles/sas/
  expecially Dr John S. Thompson.

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  University of Bristol – J.E. McGeehan
  Stanford University – A.J. Paulraj
  Nortel – Chris Ward.

Vision for 3rd Generation Systems

Three distinct data services:

- *144 kbit/s* to vehicular mobile users with omni or sectored base stations
- *384 kbit/s* to pedestrian and indoor users with base station array processing
- *2 Mbit/s* for indoor desktop users – may use both base station and mobile array processing receivers to achieve reasonable user capacity