TOSHIBA-TREL

Principles of Spread Spectrum and CDMA

Mike Fitton

Overview of Presentation

- Why consider Spread Spectrum ?
- What is Spread Spectrum & CDMA ?
- Frequency Hopping Spread Spectrum
  - Impact of channel
  - Current systems
- Direct Sequence Spread Spectrum
  - Spreading Codes
  - Analytical Performance Model
  - Rake Processing
  - Near Far Effect (Power Control)
  - Handover
- Conclusions & Discussion

Why Consider Spread Spectrum ?

- Spread Spectrum has been adopted as the air interface standard for 3rd Generation Mobile Systems (IMT2000):
  - Europe (ETSI): UMTS (W-CDMA & TD-CDMA)
  - Japan (ARIB): Wideband CDMA
  - USA (TIA TR45.5) CDMA 2000
- 2nd Generation standard deployed in US and Korea
  - IS95 (Qualcomm CDMA)

What is Spread Spectrum?

TOSHIBA-TREL

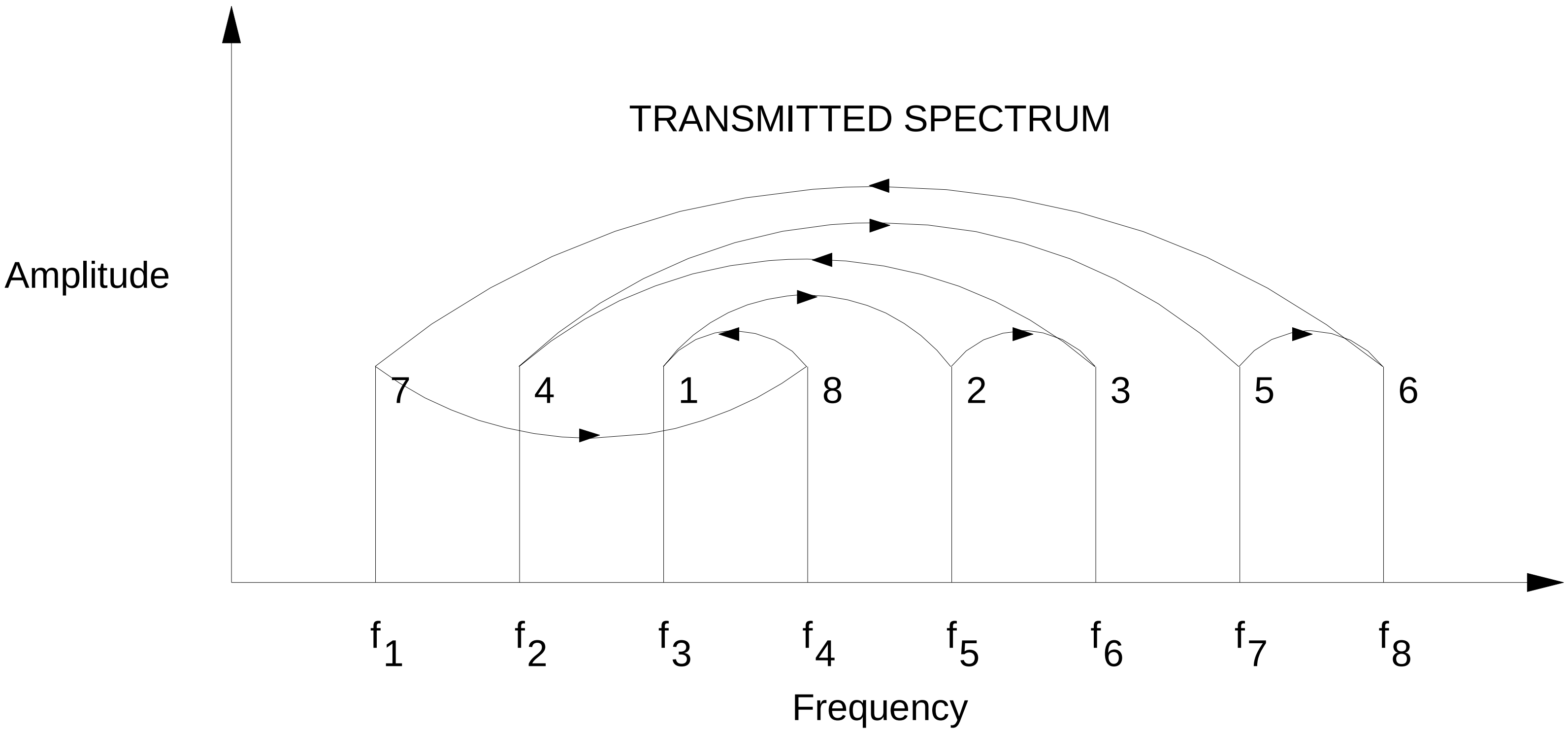
Frequency Hopping Spread Spectrum

Classification of Spread Spectrum Systems

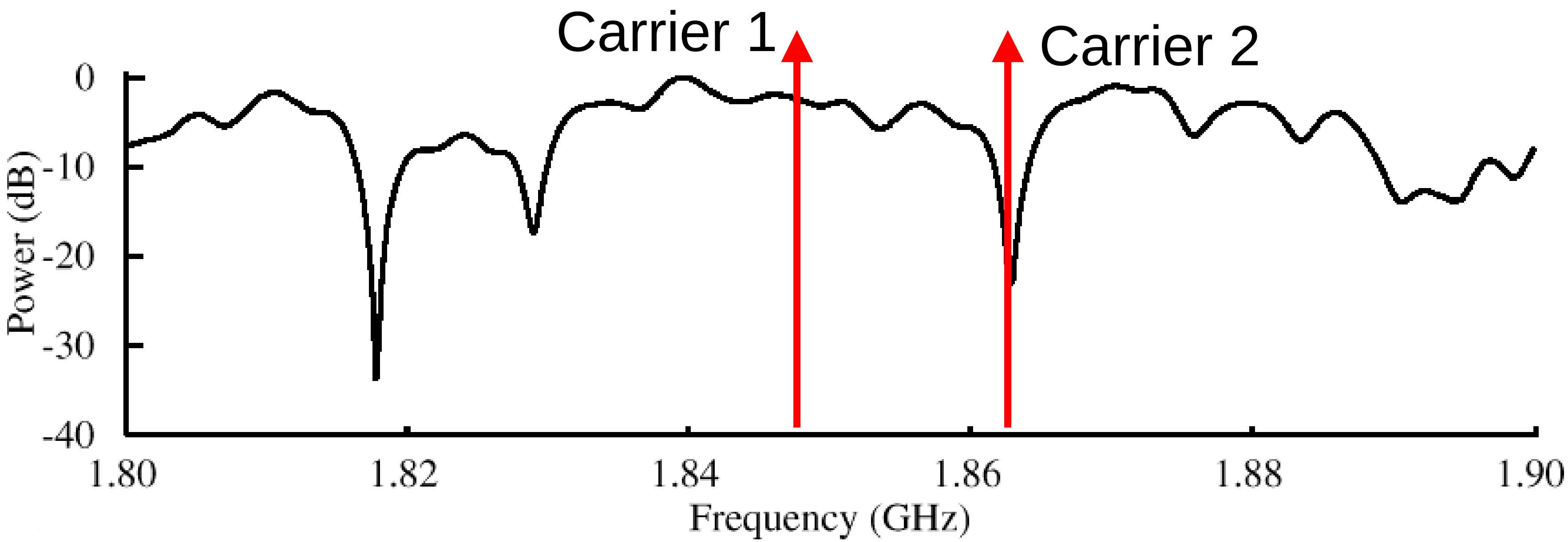
Frequency Hopping (FH)

- Narrow band message signal is modulated with a carrier frequency which is rapidly shifted
- The hop frequency is indicated by a spreading function.
- This spreading function is also available at the receiver and enables it to retune to the correct channel for each ‘hop’.

Frequency Hopping



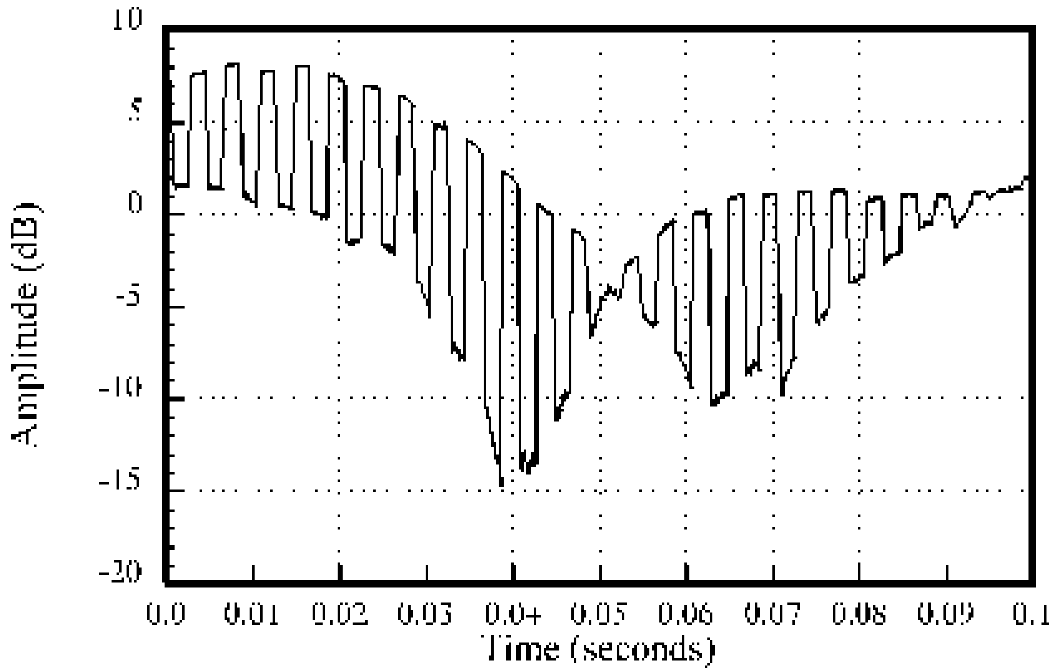
The effects of frequency hopping



- inherent *frequency* diversity
- *Interference* diversity

TOSHIBA-TREL

The effects of frequency hopping



- Randomises the propagation channel which is observed

Hop rates in an FH system

- Fast frequency hopping
  - Data symbol spread over several hop frequencies
  - *Symbol diversity*
  - Very resistant to jamming and interference, often used in military systems
- Slow frequency hopping
  - Several data symbols on each hop frequency
  - *Codeword diversity* with interleaving
  - More likely to have successful retransmission with ARQ
  - Less complex

Current FH system

- Bluetooth Wireless Personal Area Network.
  - Robust to interference (ISM band).
  - Maximise likelihood of successful retransmissions.
  - 1,600 hops/second.
  - Based on IEEE 802.11 WLAN specifications.
- Frequency Hopped Spread Spectrum is a candidate system for Wireless Local Loop.
- The GSM specification includes the possibility of full or limited frequency hopping.
  - FH randomises the interference observed and eases frequency planning.

Direct Sequence Spread Spectrum

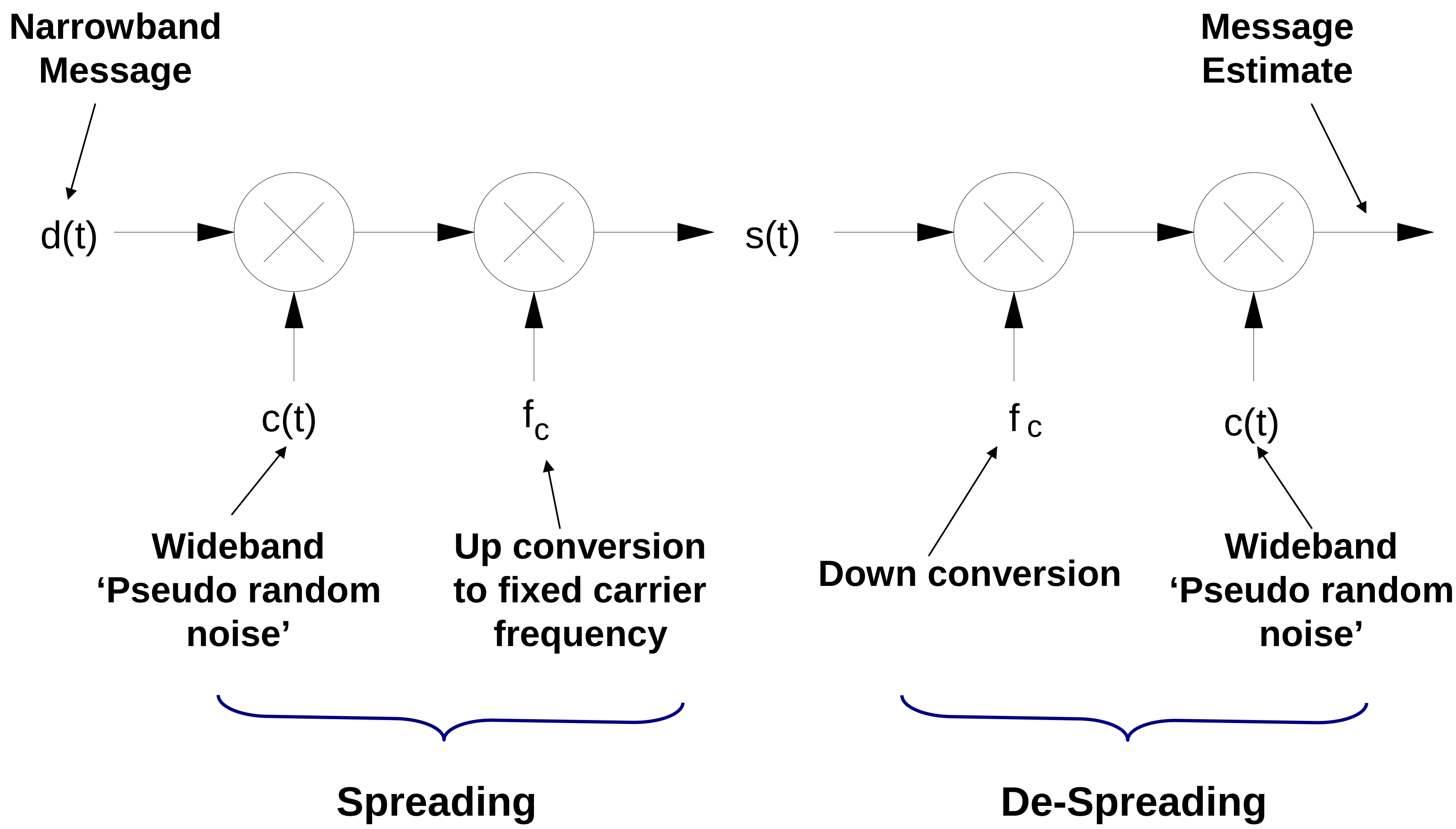
Classification of Spread Spectrum Systems

Direct Sequence (DS)

- Secondary modulation in the form of *pseudo-noise* is applied to an already modulated narrowband message, thereby *spreading the spectrum*.
- At the receiver, the incoming waveform is multiplied by an identical synchronised spreading waveform in order to recover the message.

TOSHIBA-TREL

Direct Sequence Spread Spectrum



Data and spreading modulation

- Data modulation
  - Uplink: generally BPSK (data only) or QPSK (data on I and control information on Q)
  - Downlink: QPSK (half channels on I and half on Q)
- Spreading modulation (called *secondary modulation*)
  - Choice depends processing gain required, available bandwidth (normally BPSK or QPSK).
  - Certain schemes are more tolerant to amplifier non-linearities
  - For PSK modulated signal it is assumed that at least a bandwidth of at least 88% of the chipping rate must be transmitted (3dB point)
  - MSK can be utilised to confine the power spectral density

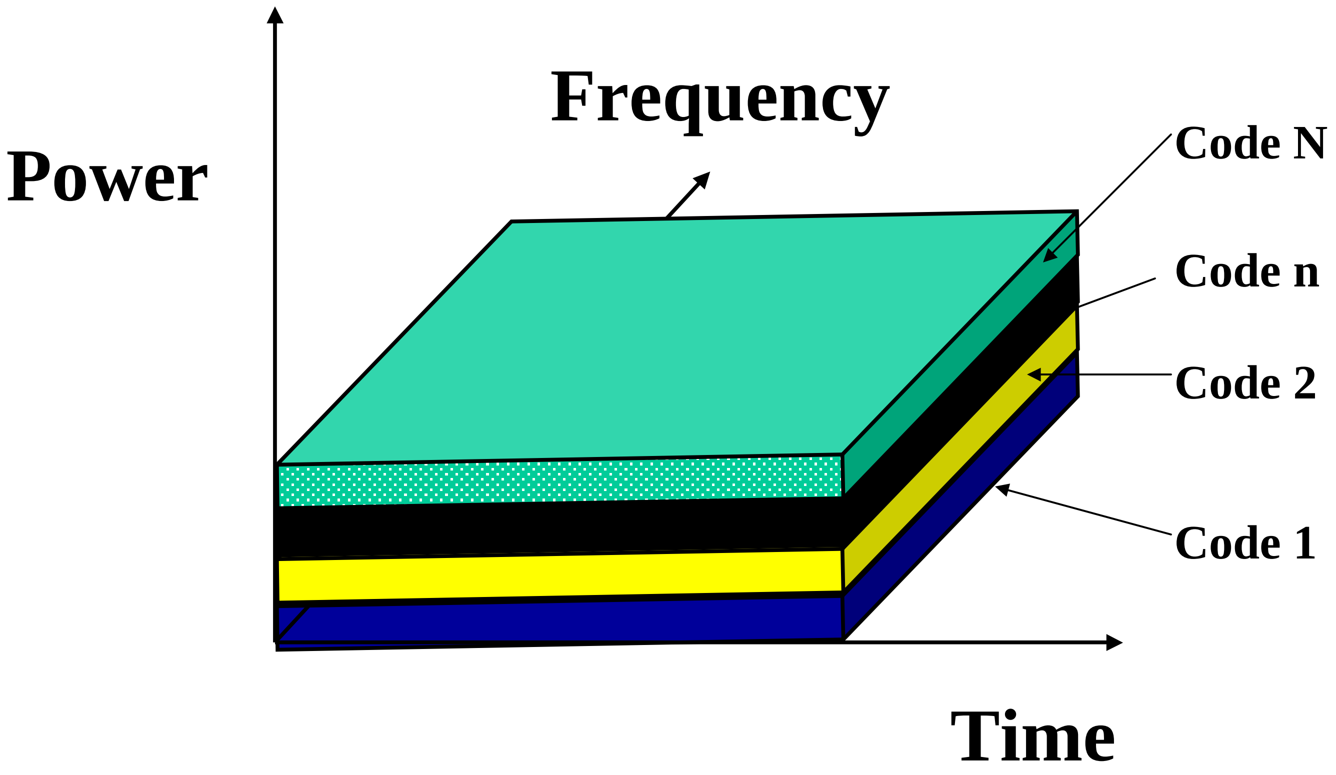
Spreading Codes

- Maximal length sequences
  - good auto- and cross-correlation
  - small code set
- Gold codes and Kasami sequences are derived from M-sequences with similar correlation properties, and a larger code set.
- Offsets in a long code (e.g. an m-sequence) can be employed if the mobiles are synchronised (as is used in IS95).

Orthogonal Spreading Codes

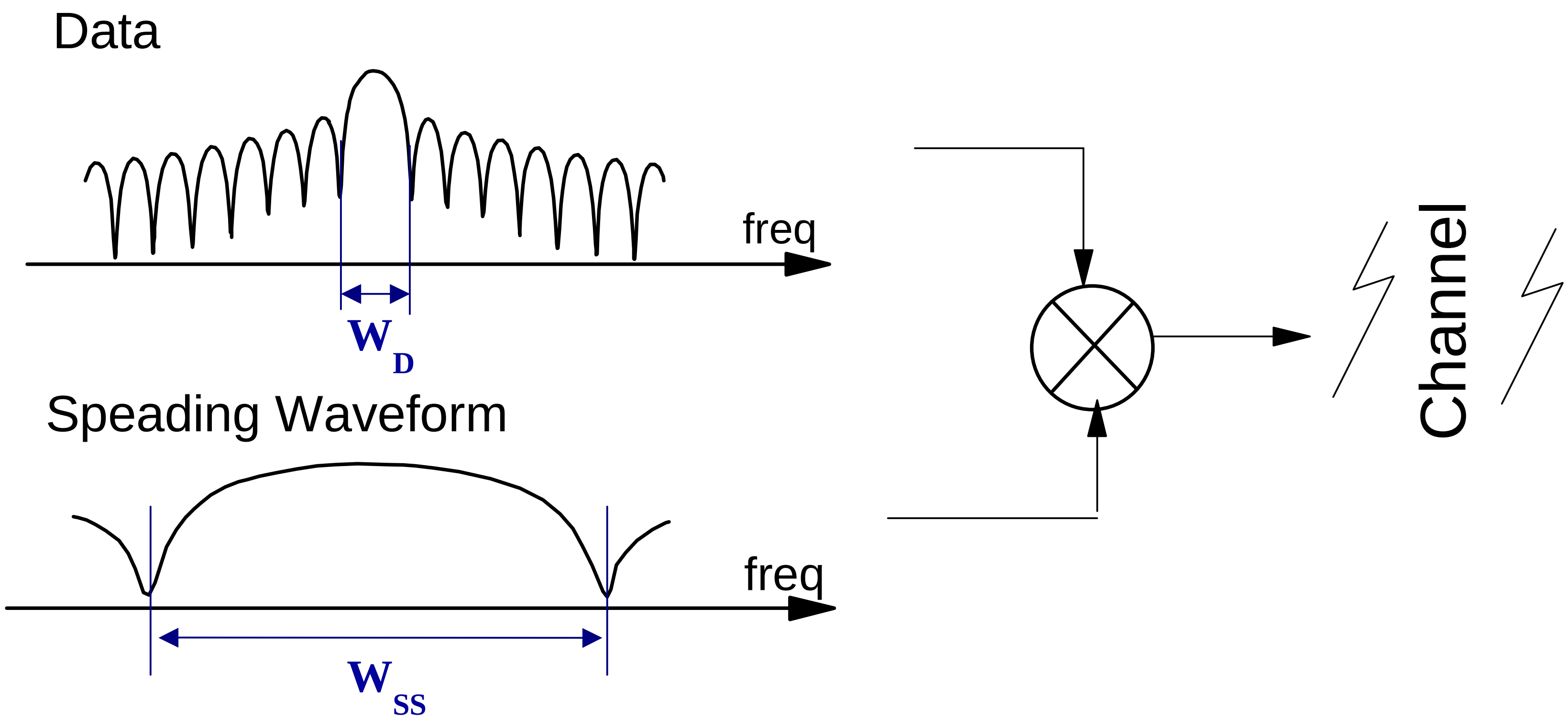
- Walsh and Hadamard sequences
  - zero correlation between codes when aligned
  - cross-correlation non-zero when time shifted
  - fixed spreading factor (codes of different length are not orthogonal)
- Orthogonal Variable Spreading Factor (OVSF) codes
  - permit orthogonal codes for different rate services
- Both types of code lose orthogonality when shifted due to channel dispersion
  - e.g. 40% loss of orthogonality in a large macrocell

Multiple Access



Code Division Multiple Access: CDMA

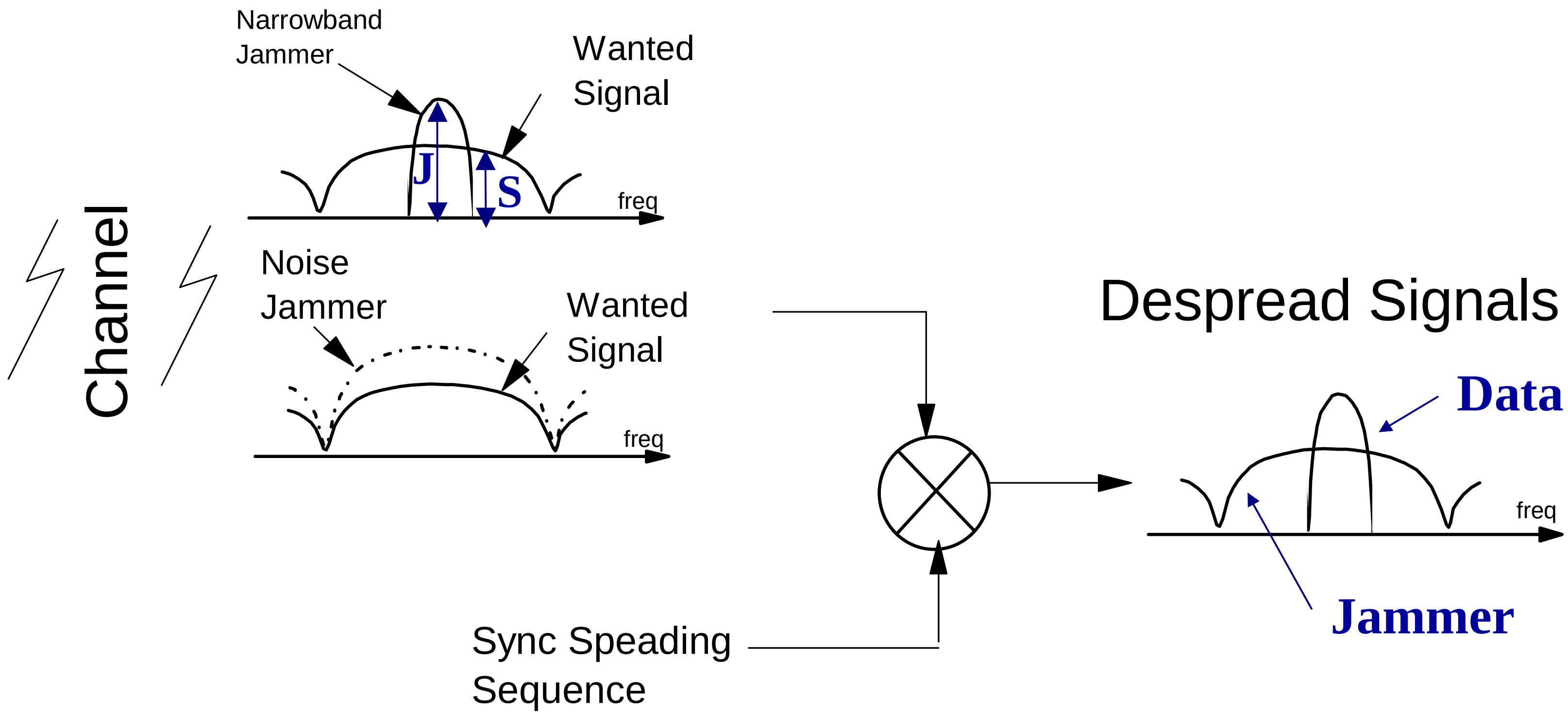
Processing Gain in Direct Sequence



$$\text{Processing Gain, PG} = \frac{W_{SS}}{W_D} = \frac{R_C}{R_D} = \frac{T_D}{T_C}$$

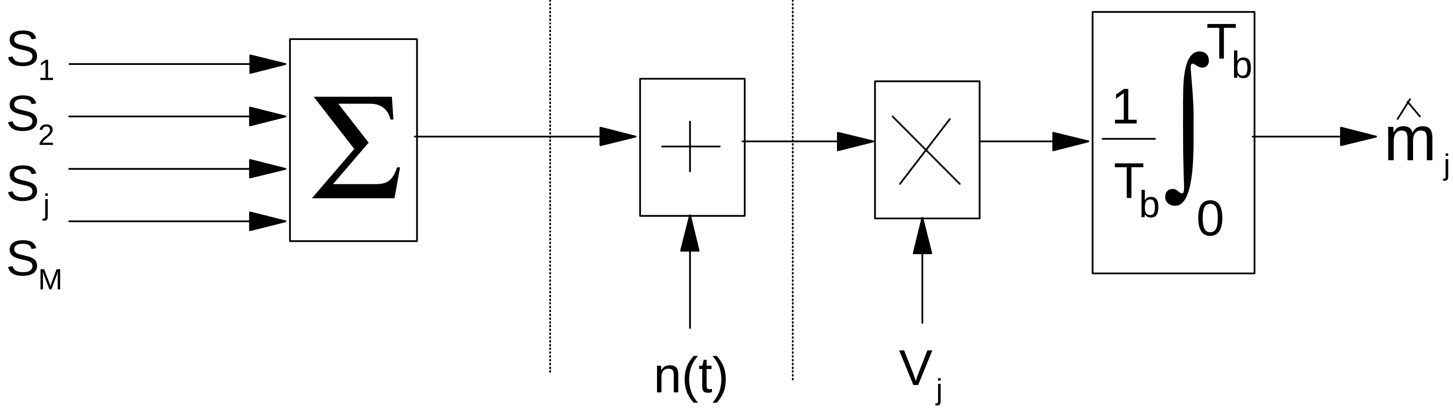
TOSHIBA-TREL

Processing Gain in Direct Sequence



$$\frac{E_b}{N_0} = \frac{S T_D}{J/R_C} = \frac{R_C}{R_D}\frac{S}{J} = PG\ S/J$$

Multi-User DS/SS System - CDMA



Users | Channel | Receiver for jth user

$$N_0' = N_0 + (M-1)E_b / PG$$

$$\frac{E_b}{N_0'} = \frac{E_b / N_0}{1 + \frac{(M-1)}{PG} E_b / N_0}$$

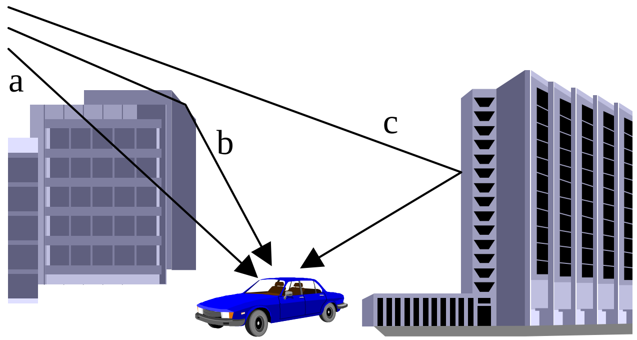
$$M = PG\left(\left(\frac{N_0'}{E_b}\right)_M - \frac{N_0}{E_b}\right)$$

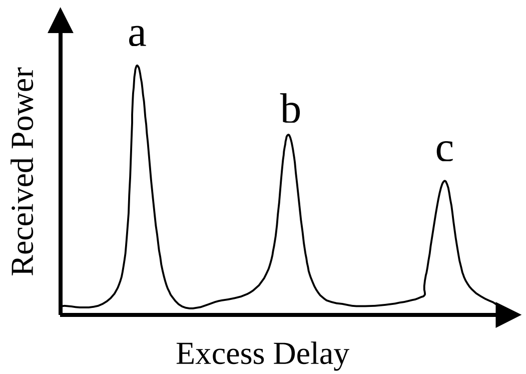
$$\text{Bandwidth Efficiency} \propto 1 \Big/ \frac{E_b}{N_0'}$$

Theoretical CDMA Capacity

- DS-CDMA capacity is inversely proportional to the energy per bit per noise power density which is tolerated
- A standard DS-CDMA system is *interference limited* by intra-cell interference
- Therefore increase capacity by:
  - voice activity detection
  - antenna sectorisation
  - adaptive antennas
  - interference cancellation

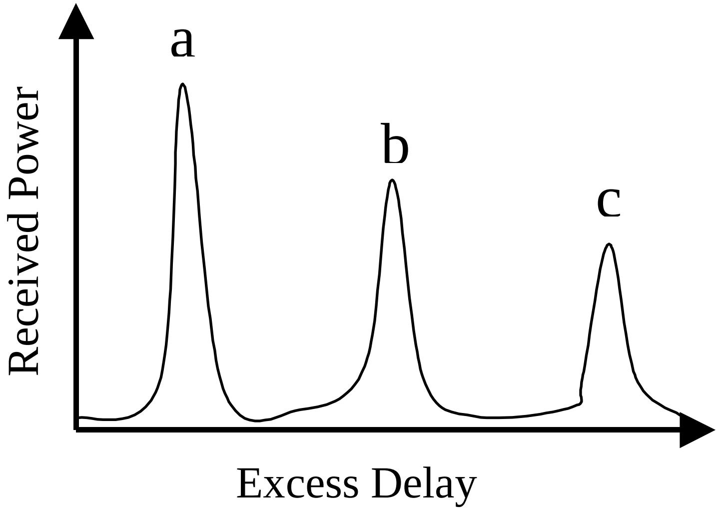
The Multipath Environment





- The received signal is made up of a sum of attenuated, phase-shifted and time delayed versions of the transmitted signal.
- Propagation modes include diffraction, transmission and reflection.

Path diversity in the multipath environment

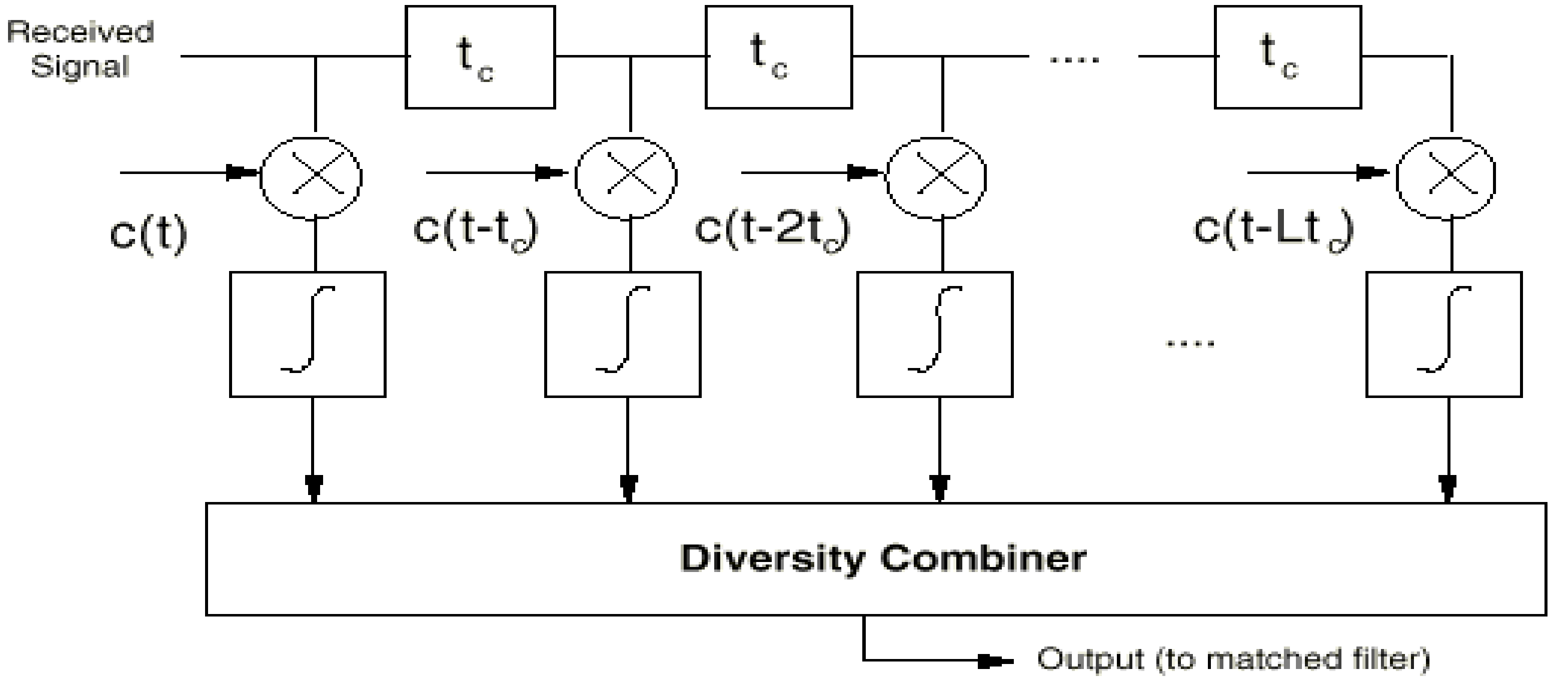


$$L_m \leq \frac{T_m}{T_C} + 1$$

- Path diversity can be exploited by separating out the multipath components, co-phasing and summing them.
- Number of paths resolved (Lm) depends on the total multipath delay (Tm) and the chip period (Tc)

TOSHIBA-TREL

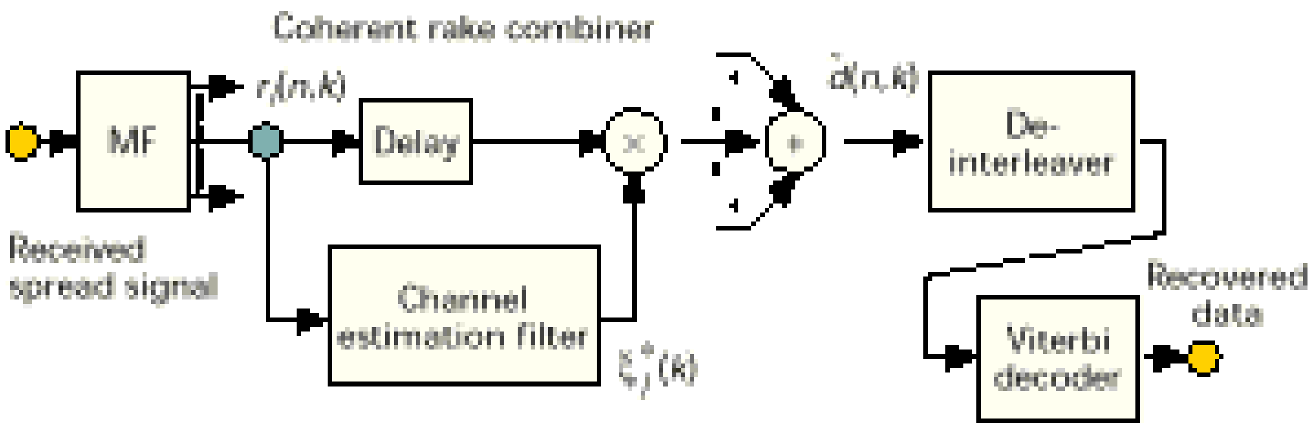
RAKE receiver



- One method of realising path diversity is with a RAKE and a bank of correlators

TOSHIBA-TREL

Coherent RAKE receiver structure



- A RAKE receiver can also be visualised as a matched filter (which resolves the propagation paths) and a channel estimation filter (to recover coherent channel information)

* Reproduced from Adachi et al in IEEE Comms magazine September 1997

TOSHIBA-TREL

Diversity and diversity combining

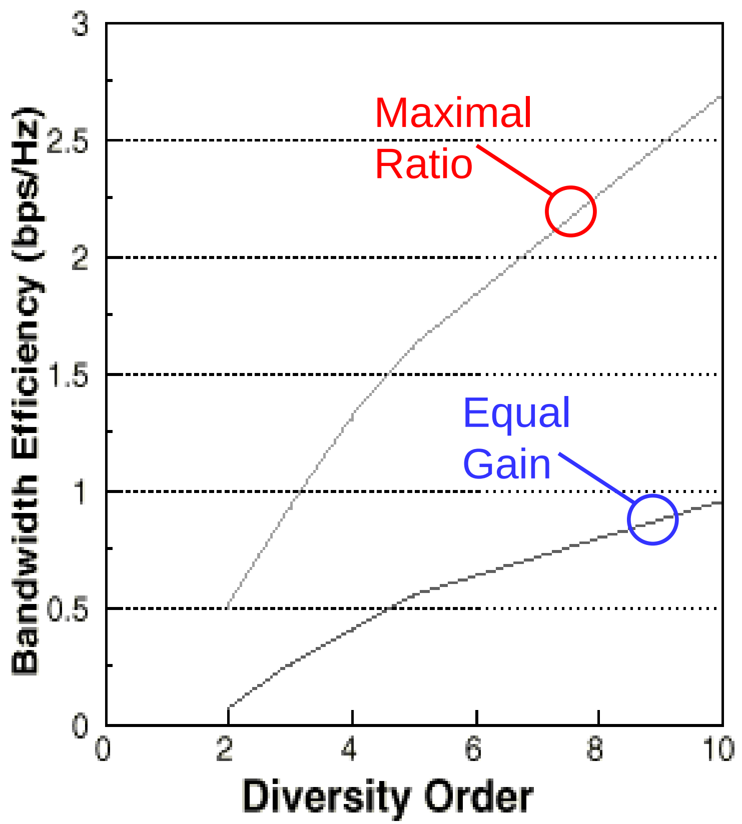
- Diversity: providing multiple versions of the transmitted signal. Commonly:
  - multiple antennas
  - multiple paths
- Diversity combining

pre-detection

  - *switched*: blindly switch to another
  - *selection*: best branch is chosen
  - *equal gain combining*: all branch summed
  - *maximal ratio*: branches summed and weighted depending on their quality

post-detection

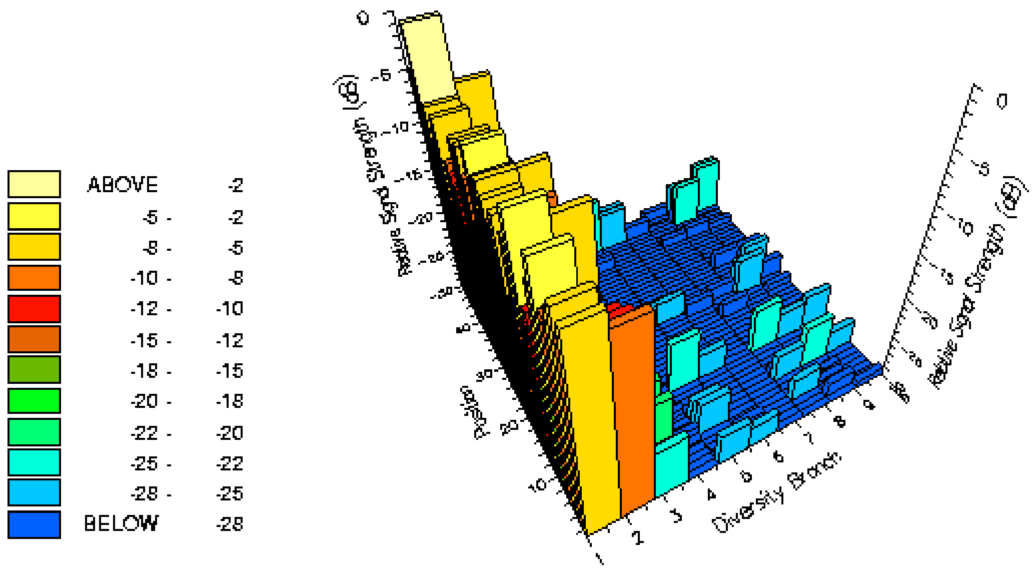
Improvement with increased diversity order



- Significant improvement in spectrum efficiency occurs with increasing diversity order (path diversity in this case).

TOSHIBA-TREL

Path diversity at low chip rates

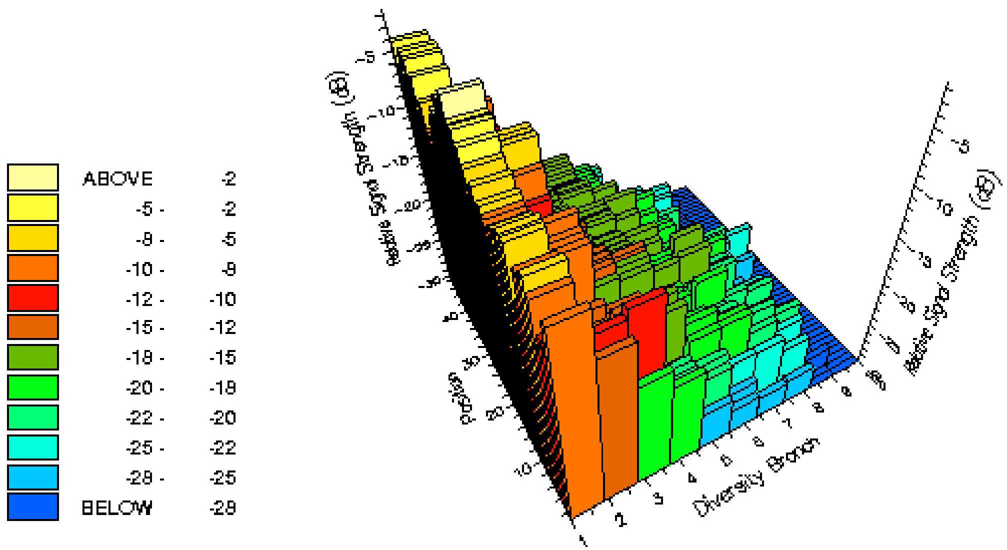


- At 1.25Mcps (IS95) only one or two bins are available for combining.
- Considerable variation in each bin due to the vector summation of many paths.

* Reproduced from M.Beach and S.Allpress, Radiowave Propagation, IEE Press

TOSHIBA-TREL

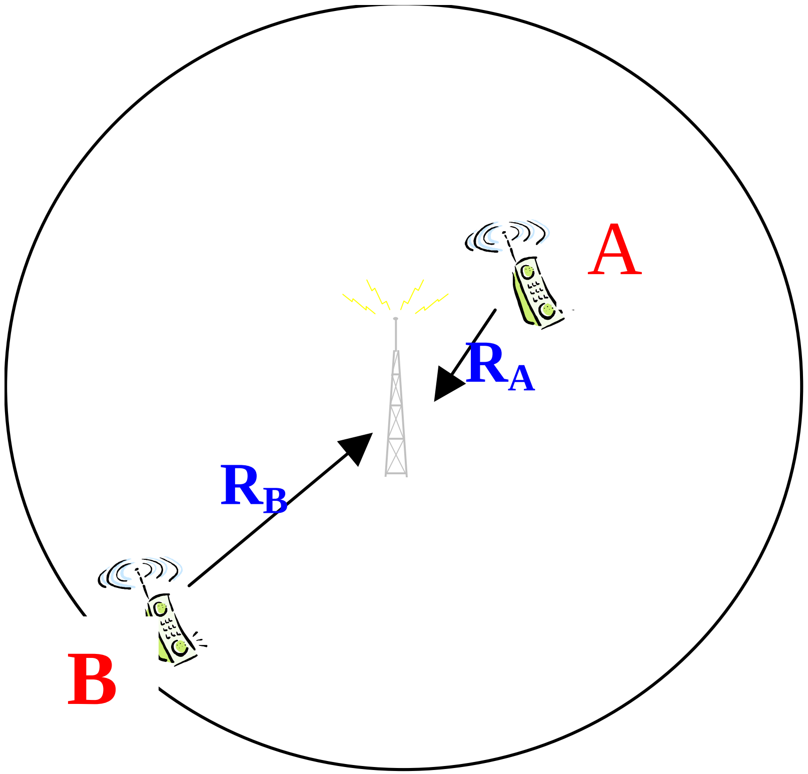
Path diversity at higher chip rates



- At 10Mcps more bins are available for combining, improving performance.
- Fading in each bin is more deterministic as less paths are present.

* Reproduced from M.Beach and S.Allpress, Radiowave Propagation, IEE Press

The near-far effect in CDMA

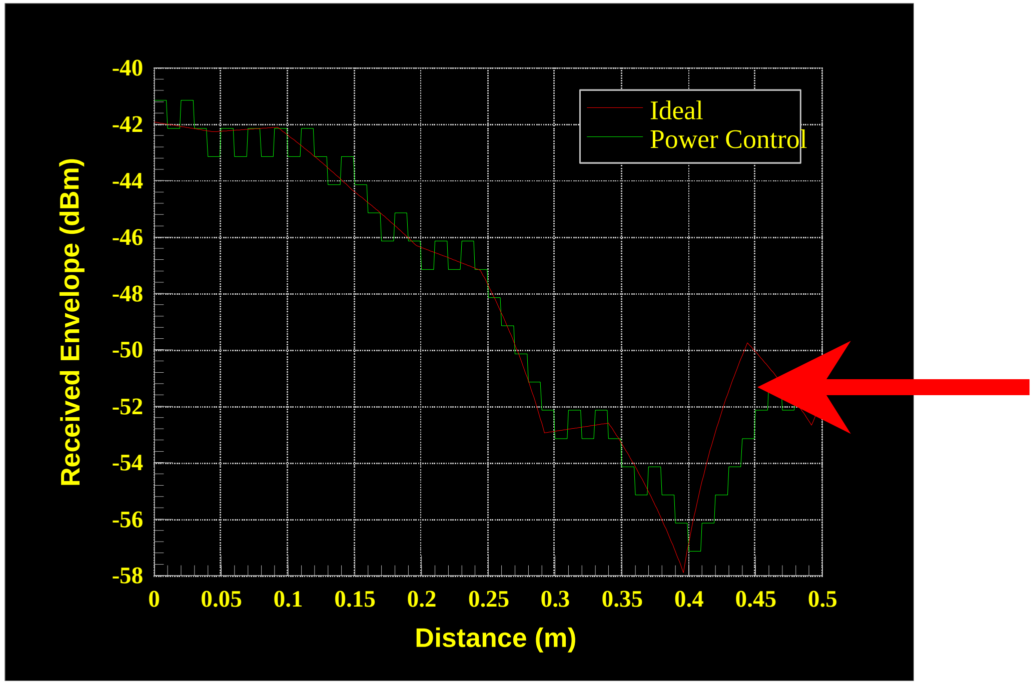


- Everyone on same frequency at the same time.
- A MS close to the BS will “drown out” other MSs unless it reduces it’s power.
- Power control is required.

CDMA Power Control

- Power control required on uplink, desired on downlink.
- Open loop control can be used to remove shadowing (as the channel is reciprocal).
- Closed loop control is required to remove the fast fading
  - BS receives MS signal and calculates the SIR
  - BS sends MS a transmit power control (TPC) signal to increase or decrease its power
- TPC issues include rate and step size

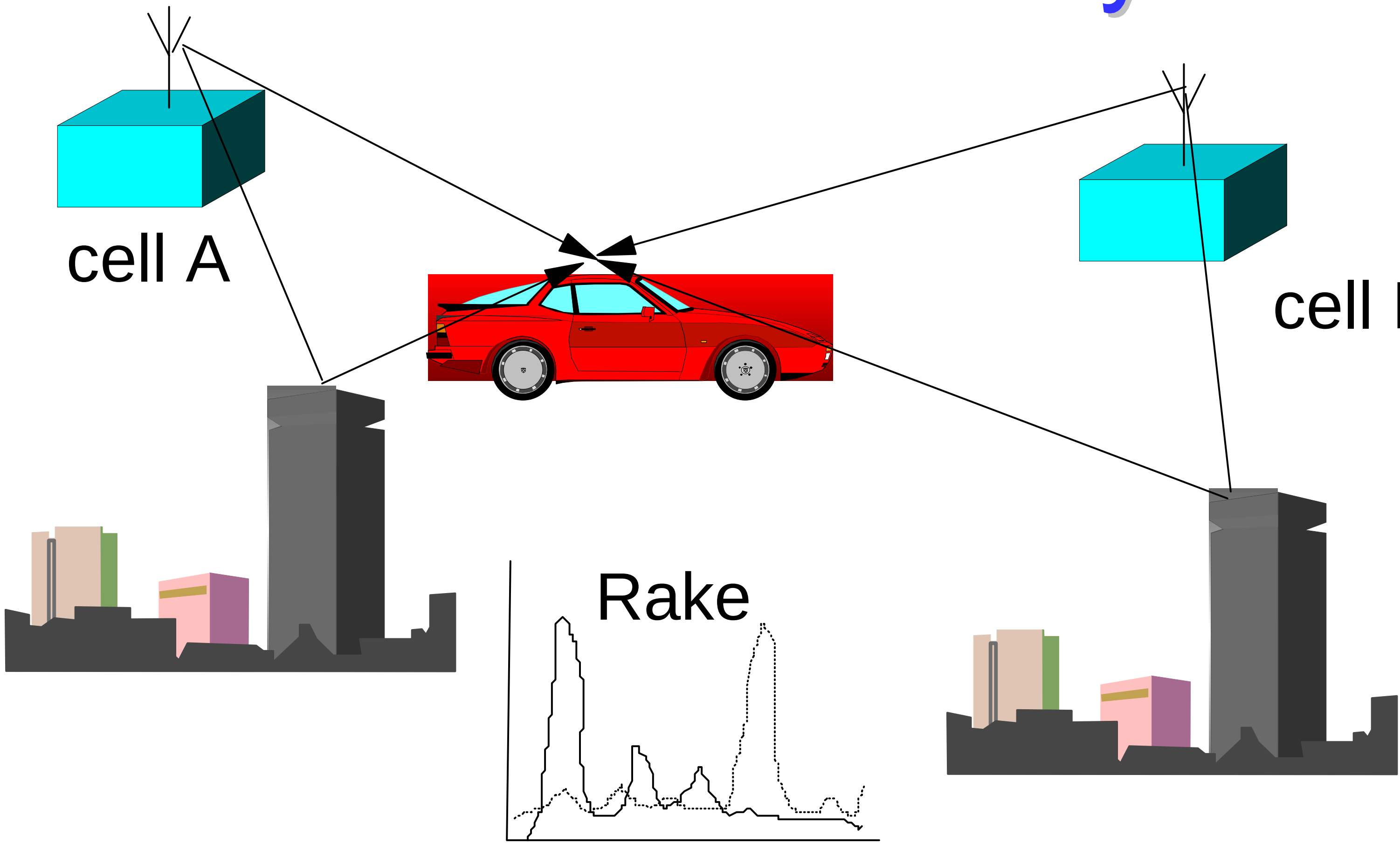
Uplink closed loop power control algorithms



Insufficient tracking of changes

- Sigma-delta scheme used
- Command rate must be sufficient to track channel changes
- Trade-off in step size between tracking and accuracy

Handover & Mobility



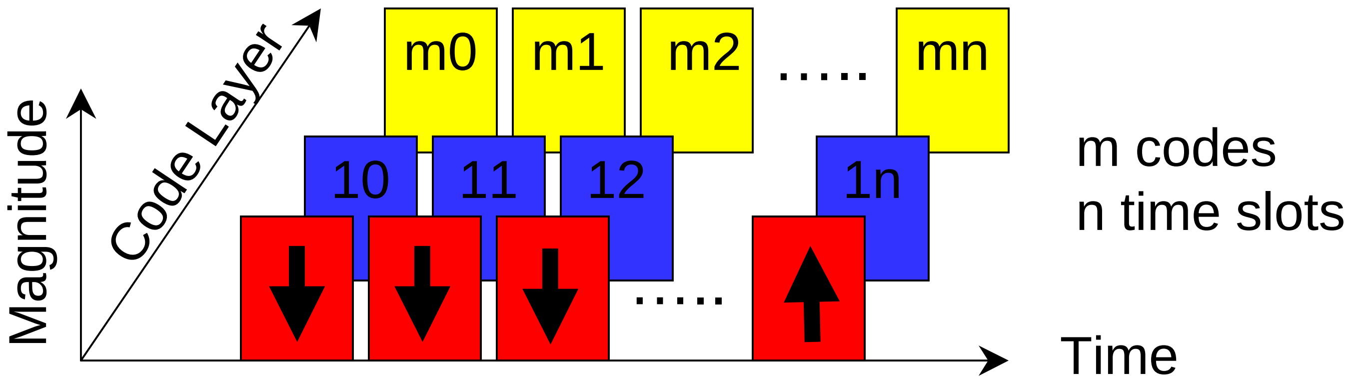
W-CDMA in UMTS

W-CDMA is used in FDD mode in UMTS

- On the downlink it is possible to use orthogonal spreading codes to reduce interference. A scrambling code is used to separate the cells
- On the uplink, low cross correlation codes are used to separate the mobiles. A single mobile can use *multi-code* transmission: each service is mapped onto several bearers, each of which is spread by an orthogonal code.

TD-CDMA (UMTS TDD mode)

- There are a number of time slots, and a number of codes in each time slot. For example 16 time slots and 8 or 9 codes in UMTS TDD mode.



- Codes are orthogonal on DL
- UL codes must either be synchronised or some form of multiuser detection used in BS

Comparison of DS and FH CDMA

- DS-CDMA
  - Flexible support of variable data rate
  - High capacity is possible with enhancements (interference cancellation, adaptive antennas, etc)
  - Suffers from near-far effect – power control required
- FH-CDMA
  - Suitable for ad hoc networks (no near-far problem)
  - Robust to interference
  - Limited data rate

Conclusions

- Spread spectrum systems provide a robust means of communication
  - FH and DS are used for WLANs in the ISM band at 2.4GHz due to their interference resistance
- It can be applied to multi-user systems in the form of Code Division Multiple Access
  - Users share the same frequency at the same time, and are separated by their unique code.
- Both approaches are applied in many communications systems today
  - The flexibility and bandwidth of DS-CDMA make it suitable for high capacity, cellular systems supporting many applications
  - The robustness of Frequency Hopping make it suitable for ad hoc networks, such as WLAN and WPAN