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Digital Modulation: Current Wireless Techniques

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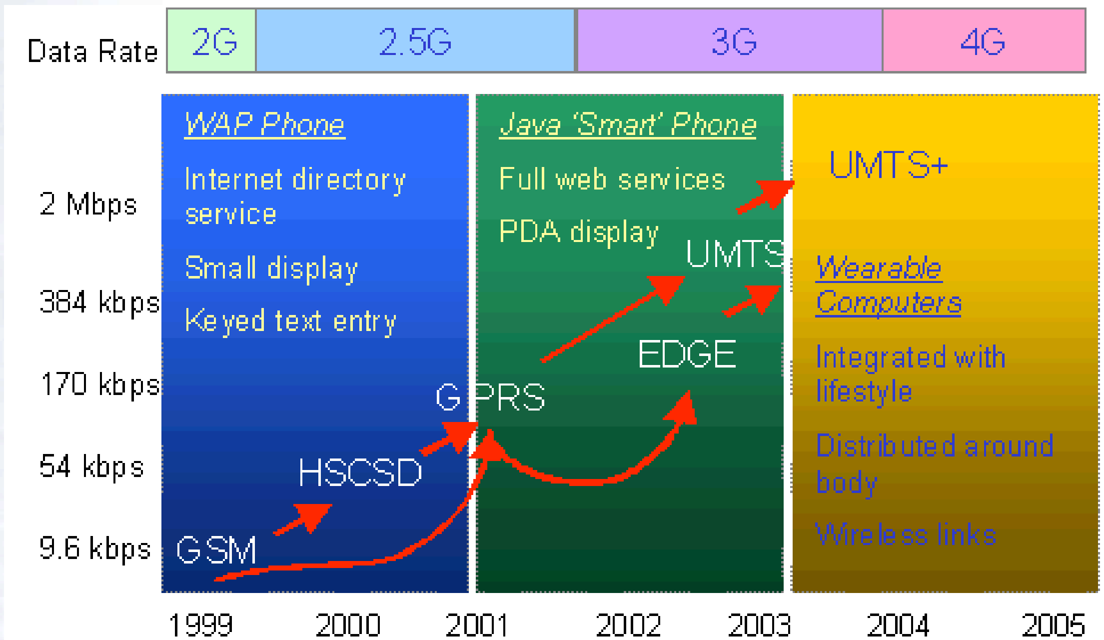
Outline of Lecture

- Personal communication system requirements
- Multiple Access Techniques
  - Frequency Division Multiple Access
  - Time Division Multiple Access
  - Code Division Multiple Access
- Wireless Technologies
  - Coding
  - Equalisation
  - OFDM
  - Diversity and Diversity Combining
  - Spread Spectrum

Evolution of personal cellular communications



- Availability of complementary wireless systems
  - Short range: wireless PAN (Bluetooth)
  - Medium range: wireless LAN, WiFi
  - Longer range: WiMAX

Multiple Access

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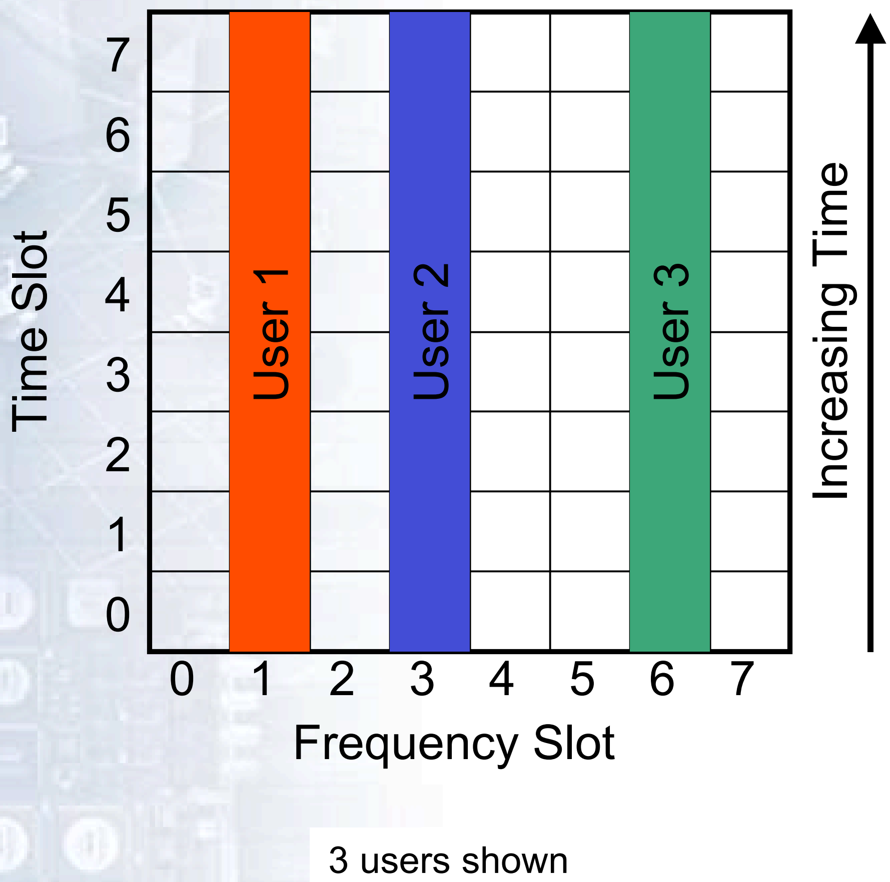
Multiple Access Requirements

A wireless communications system employs a *multiple access technique* to control the allocation of the network resources. The purposes of a multiple access technique are:

- To provide each user with unique access to the shared resource: the *spectrum.*
- To minimise the impact of other users acting as interferers.
- To provide efficient use of the spectrum available.
- To support flexible allocation of resources (for a variety of services).

Frequency Division Multiple Access (FDMA)



- Each user is assigned a unique frequency for the duration of their call.
- Severe fading and interference can cause errors.
- Complex frequency planning required. Not flexible.
- Used in analogue systems, such as TACS (Europe), and AMPS (USA).

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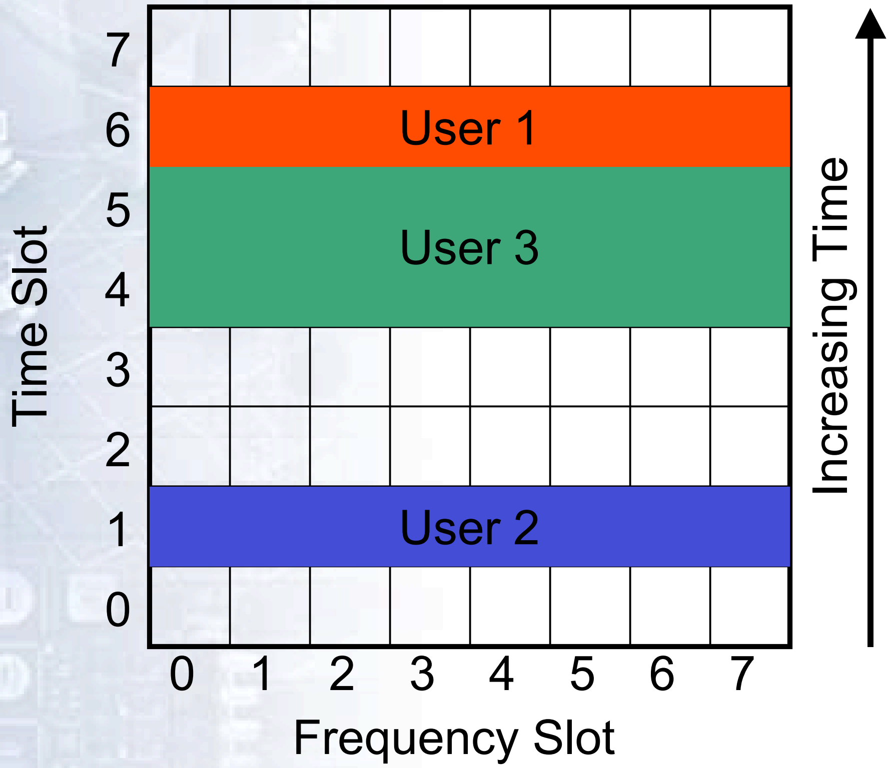
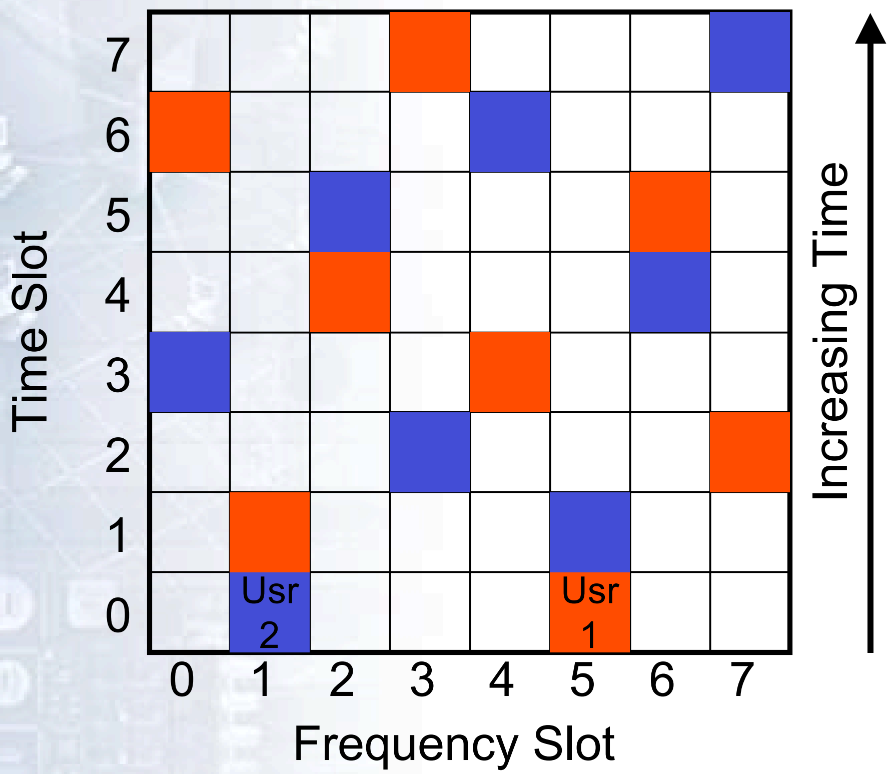
Time Division Multiple Access (TDMA)



3 users shown

- Each user can use *all* available frequencies, for a limited period. The user must not transmit until its next turn.
- High bit rates required, therefore possible problems with intersymbol-interference.
- Flexible allocation of resources (multiple time slots).
- Used in second generation digital networks, such as GSM (Europe), and D-AMPS (USA).

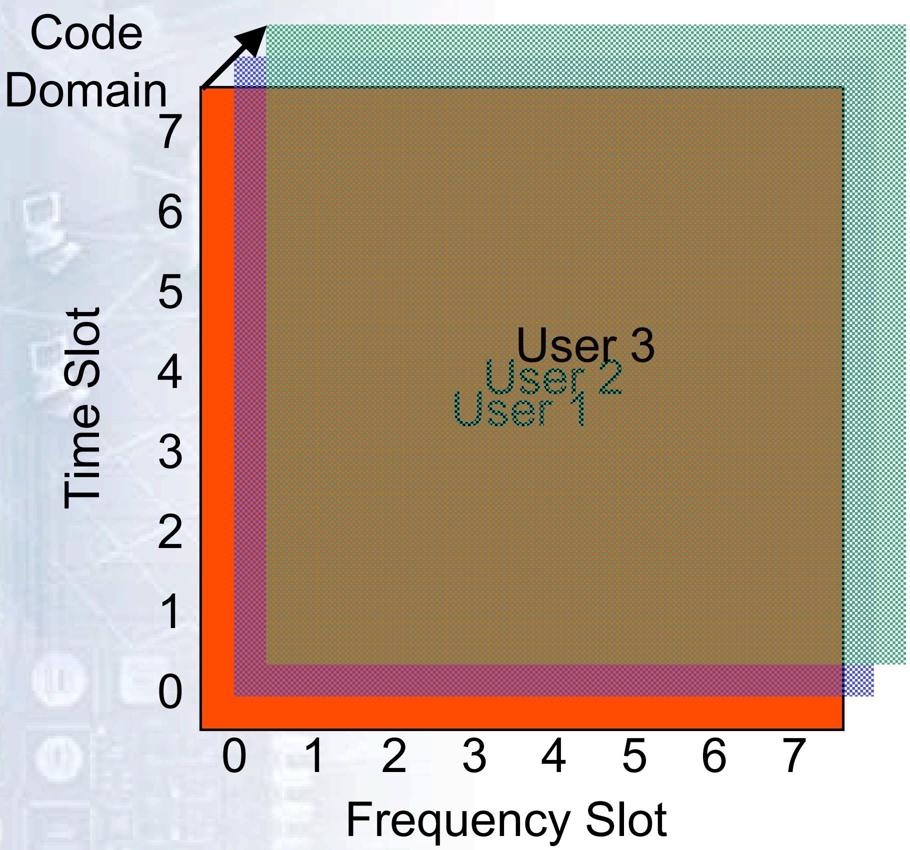
Frequency Hopping
Code Division Multiple Access (FH-CDMA)



- Each user regularly *hops* frequency over the available spectrum.
- Users are distinguished from each other by a unique hopping pattern (or *code*).
- Interference is randomised.
- Used in Bluetooth™

2 users shown

Direct Sequence
Code Division Multiple Access (DS-CDMA)



3 users shown

- All users occupy the *same spectrum* at the *same time*.
- The modulated signal is *spread* to a much larger bandwidth than that required by multiplying with a *spreading code*. Users are distinguished from each other by a unique spreading code.
- Very flexible, but complex.
- Currently used in 3G and 2nd generation IS-95

Summary of Multiple Access Techniques: The Cocktail Party

To illustrate the nature of the multiple access techniques, consider a number of guests at a cocktail party. The aim is for all the guests to hold an intelligible conversation. In this case the resource available is the house itself.

- FDMA: each guest has a separate room to talk to their partner.
- TDMA: everyone is in the same room, and has a limited time to hold their conversation (so they must talk very quickly).
- FH-CDMA: the guests run from room to room to talk.
- DS-CDMA: everyone is in the same room, talking at the same time, but each pair talks *in a different language*.

Duplex Communication

- Two way communication is called *duplex* (eg. for cellular radio). One way is called *simplex* (eg. for paging).
- The link from the base-station to mobile is the *down-link*. The link from the mobile to base-station is the *up-link*.
- The up-link and down-link can exist simultaneously on different frequencies: *Frequency Division Duplex* (FDD).
- The up-link and down-link can exist on the same frequency at different times: *Time Division Duplex* (TDD).

Wireless technologies

Coding: Forward Error Correction

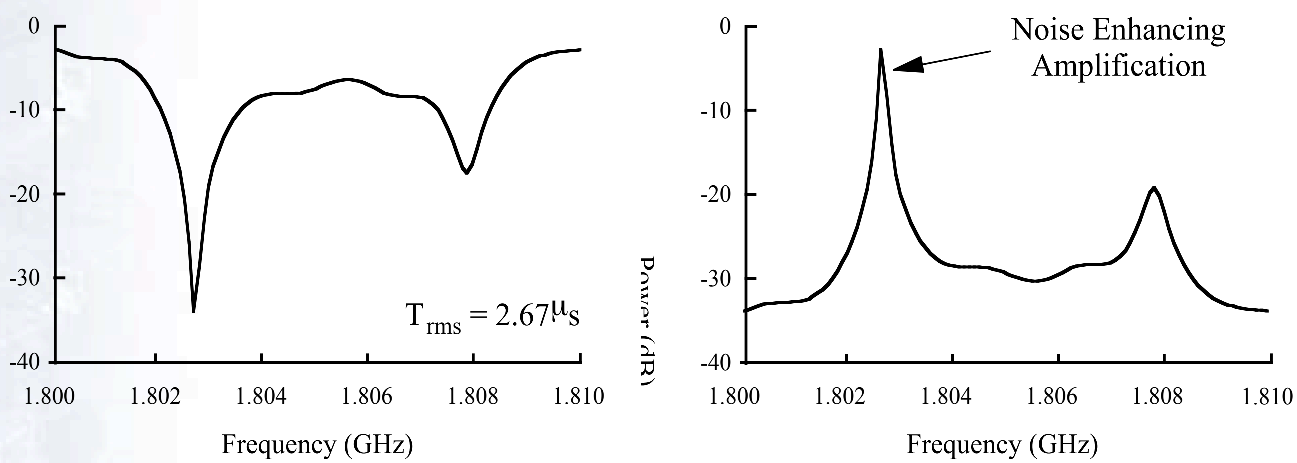
- So far we have considered the uncoded case
- It is possible to apply redundancy (in time, frequency or space) and exploit this to give error detection and error correction
- A simple example is a repetition code (1➔111)
- There are many types of coding that can be used
  - Block code
  - Convolution code (use current input and previous ones)
  - Turbo codes: use two recursive systemic encoders, and two decoders that are run iteratively)
  - Many more…
- Coding requires an overhead (e.g with a rate _ code, the information rate is half the transmission rate). May not be appropriate in all instances (e.g. in interference)

Automatic Repeat Request (ARQ)

- Detect an error in a packet, for example with a Cyclic Redundancy Check (c.f. checksum).
- Inform the transmitter of the problem (e.g. through failure to return an ACK, or using a NACK)
- Transmitter then retransmits that packet
- Many different ARQ schemes are possible

- ARQ is more appropriate for non-real time traffic (e.g. data), or isochronous traffic (where a limited number of retransmissions are permitted)
- FEC is useful for real-time traffic (e.g. voice and real-time video)

Equalisation

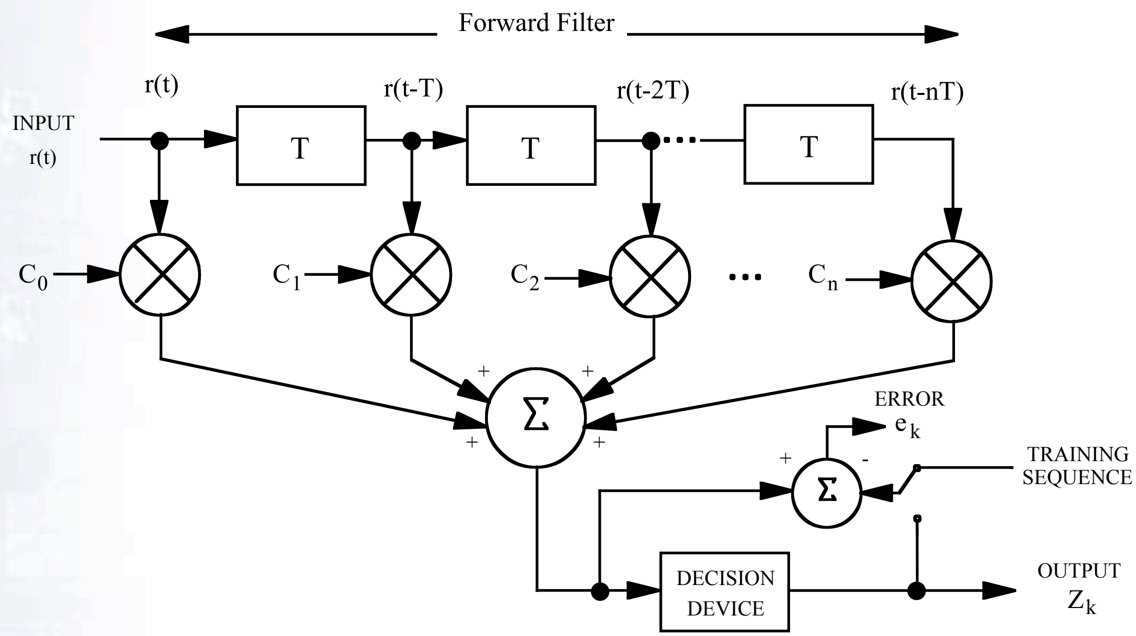


(i) Channel (Frequency Domain)

(ii) Forward Filter (Frequency Domain)

- *Frequency-selective fading* arises due to time-dispersion in the multipath channel. This type of *wideband* fading causes *irreducible* errors, unless its effects are mitigated.
- Equalisation is employed to remove the harmful frequency-selective fading. It acts as an adaptive filter, to produce an output signal with a flat frequency response. Consequently, error-free transmission at high data rates is possible.

Linear Transversal Equaliser



- The linear transversal equalisation (LTE) is one of the simplest forms of equaliser.
- The tap coefficients (C1 to Cn) are adapt to suit the current channel conditions. Normally this adaptation is done on a training sequence.
- In the presence of severe amplitude and phase distortion, the required inverse filter tends to result in an unacceptable degree of noise amplification.

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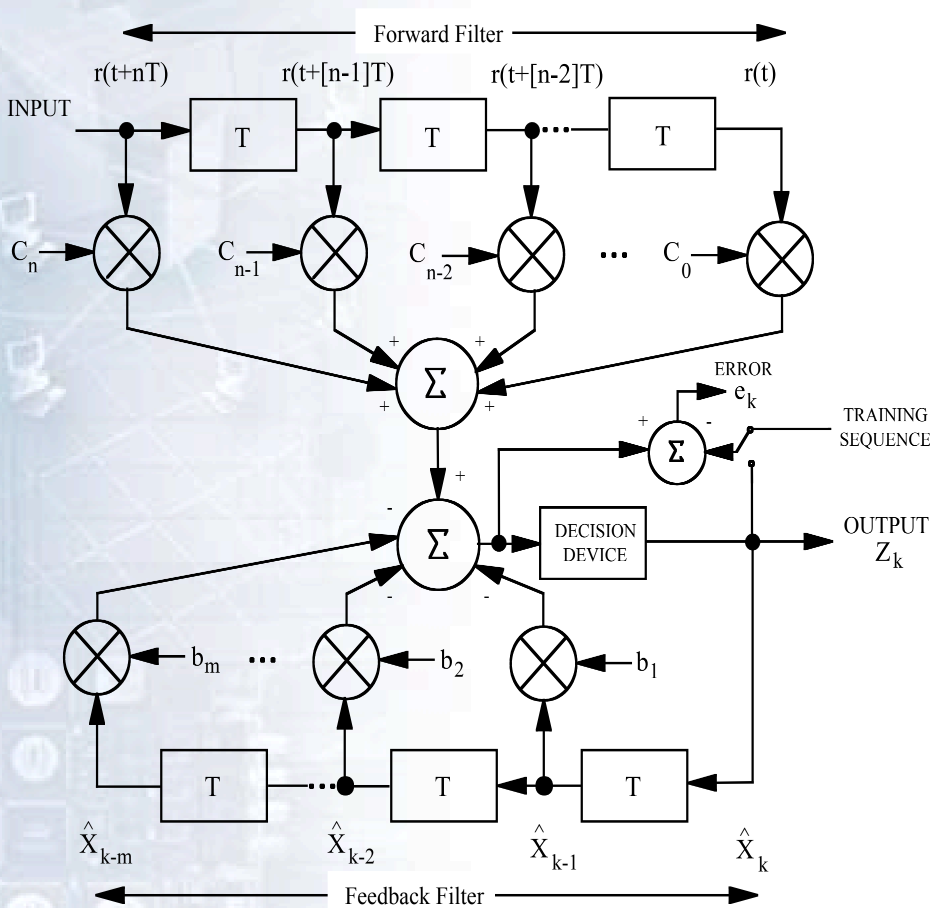
Decision Feedback Equaliser



- The equaliser output signal is the sum of the outputs of the *feedforward* and *feedback* sections of the equaliser.
- The forward section similar to the LTE
- Decisions made from the output of the equaliser are now feed back through a second filter.
- If these decisions are correct, the ISI caused by these symbols can be cancelled without noise enhancement
- However, errors made in hard decisions are fedback through the equaliser and can cause error propagation

Equalisers (cont.)

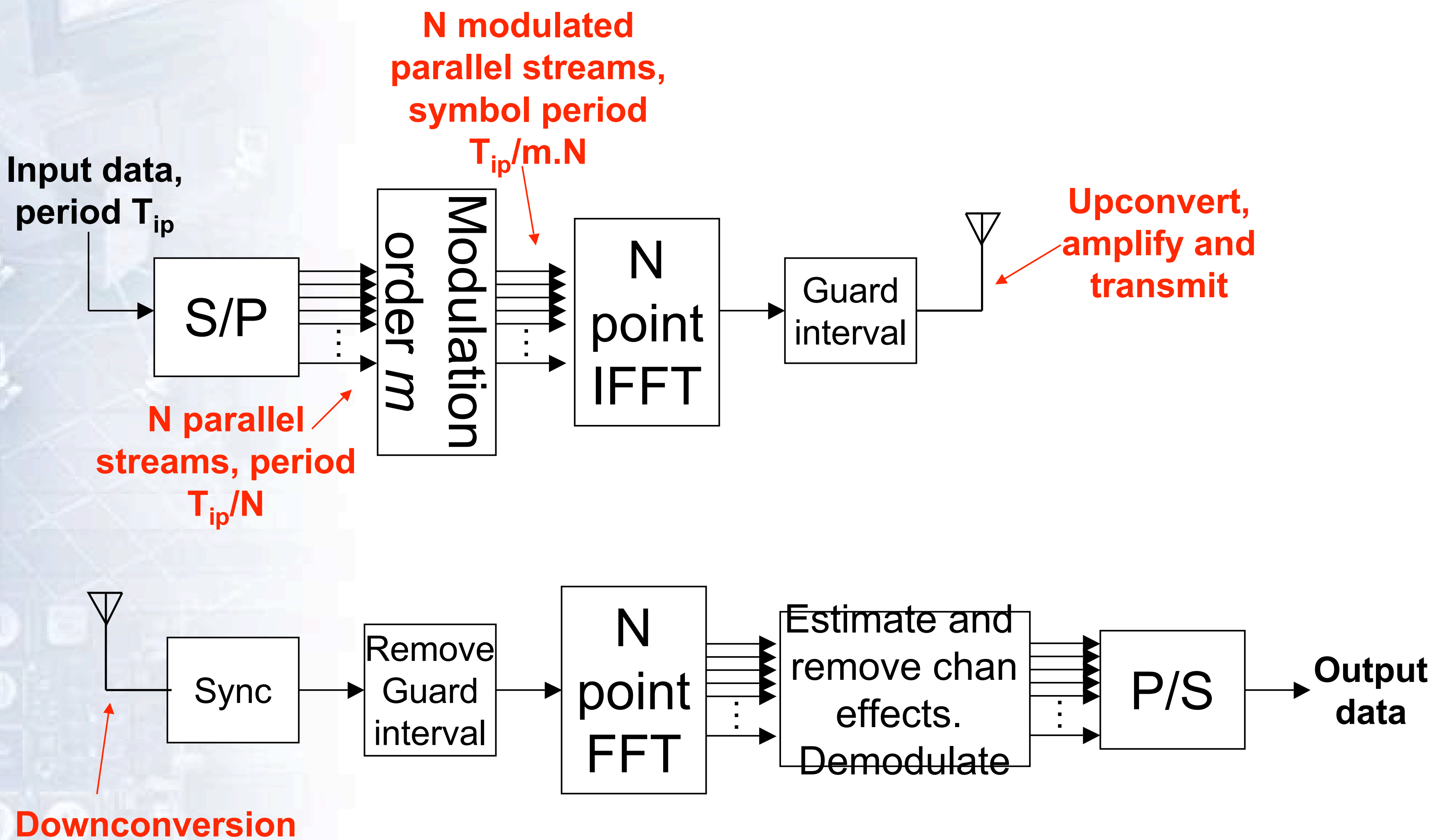
- Maximum Likelihood Sequence Estimation (MLSE or *Viterbi equaliser*) is a more complex alternative to LTE or DFE, but has good performance and is often used in GSM.

- Equaliser training for LTE, DFE and Channel Estimator with MLSE
  - LMS Gradient (less complex)
  - RLS (Kalman) algorithm (fast but computationally expensive)
- Training algorithm selection
  - Convergence speed
  - Complexity
  - Robustness to Channel Variations
  - Numerical Stability

Orthogonal Frequency Division Multiple Access (OFDM)

- Equalisation is required when the channel time dispersion become significant wrt the symbol period
- Alternatively, lengthen the symbol period (reduce the data rate) until time dispersion is no longer a problem
  - Reduce the throughput?
  - Divide the input into multiple streams and use them to modulate multiple carriers ➔Multicarrier
- OFDM is a method of implementing Multicarrier with optimal throughput and spacing of the carriers

OFDM overview



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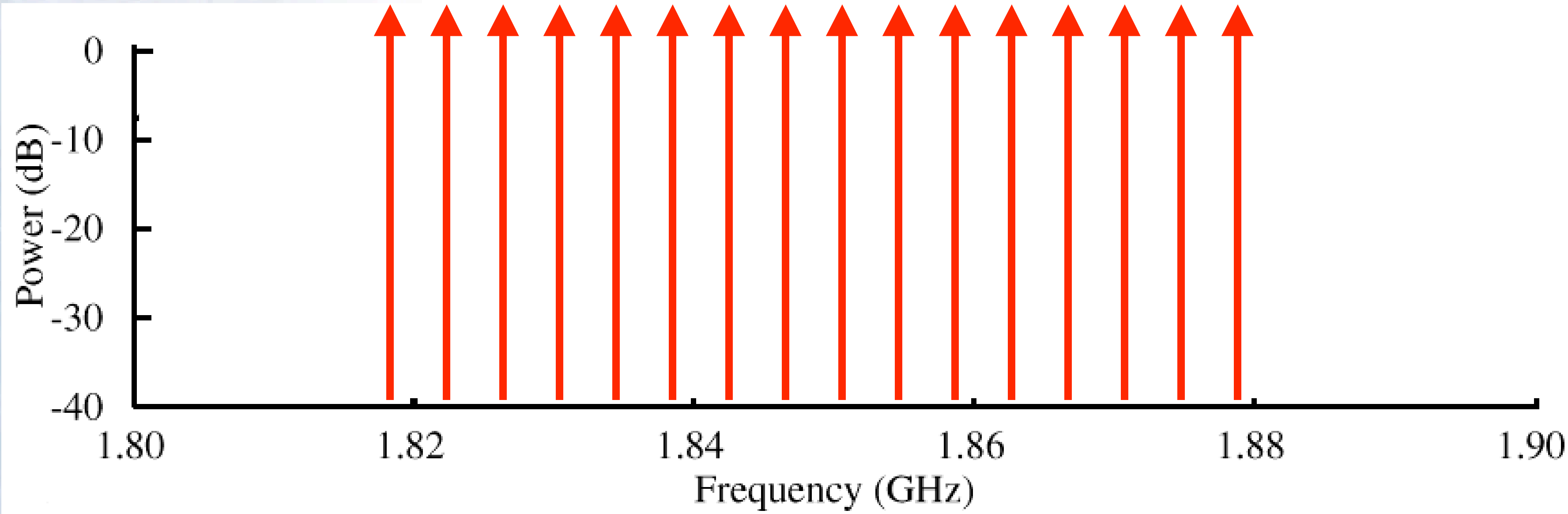
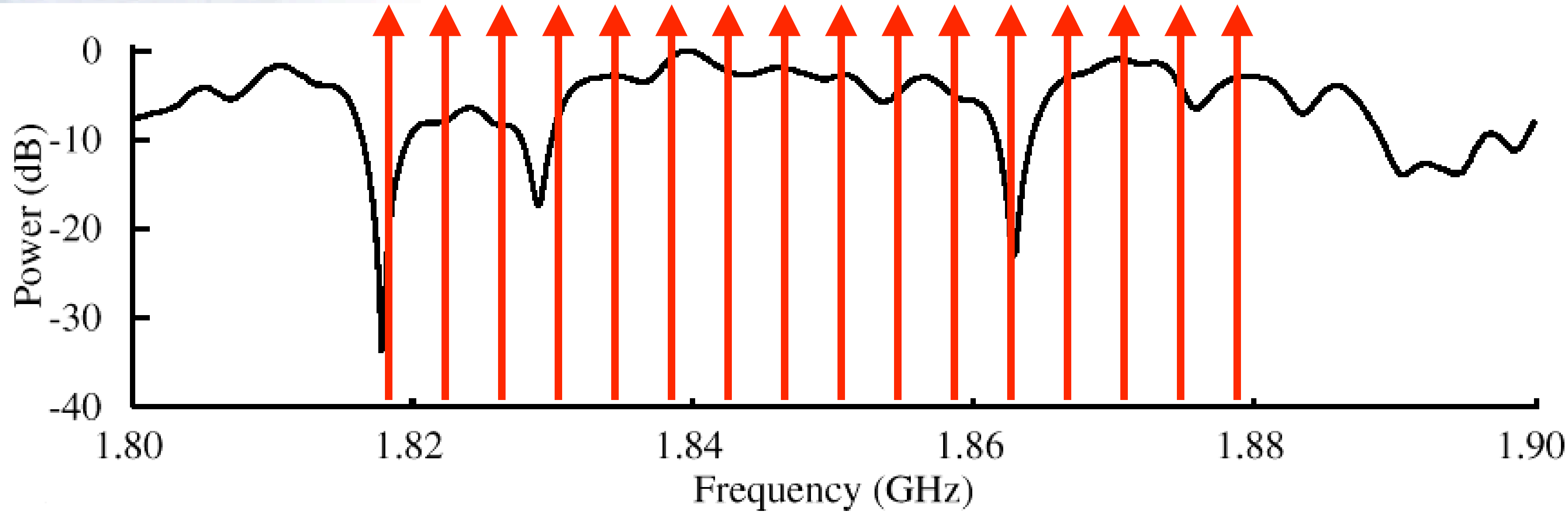
Transmitted Spectrum in OFDM

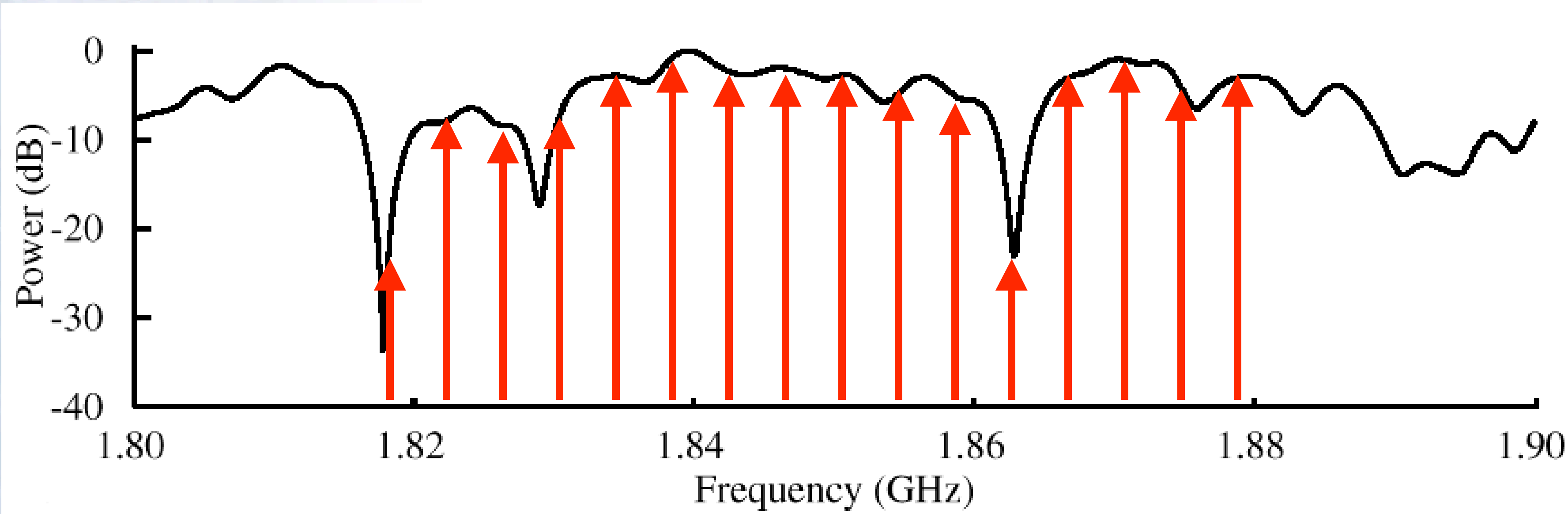


- A comb of carriers is produced, each one running at a baud rate of R_{data}/m.No_carriers

Effect of the wireless channel



Effect of the wireless channel



- The carriers are spread over the fades in the frequency domain, producing *frequency diversity*.
  - This can be exploited with e.g. coding

OFDM advantages and disadvantages

For:

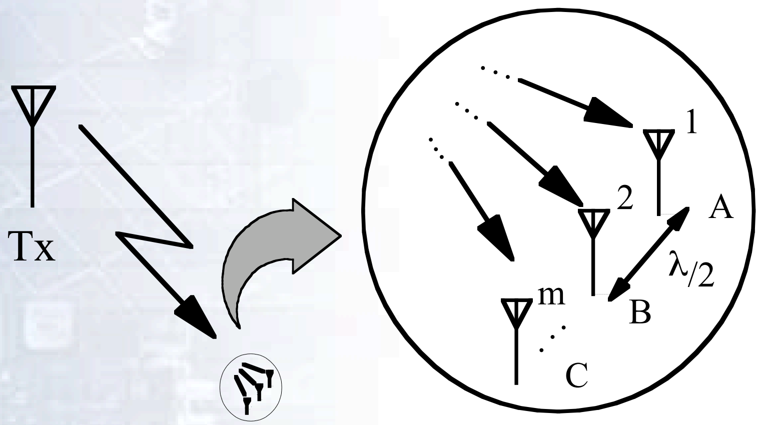
- The system is robust to channel time dispersion and exploits the nature of the wideband channel (frequency diversity)
  - Complex equalisation is not required
  - Very high data rates can be achieved
- Can be applied as multiple access (OFDMA)

Against:

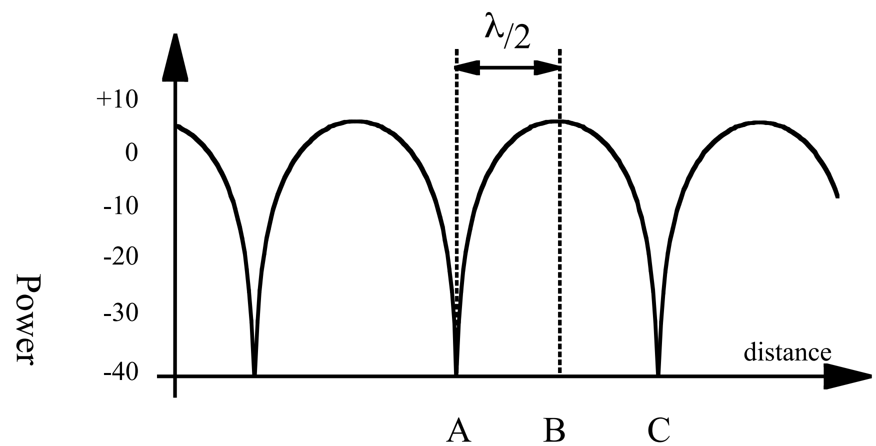
- Accurate synchronisation required
- There is an overhead associated with immunity to time dispersion – the Guard Interval
- High peak-to-mean power ratio ➔ linear amplifier required
- Limited range and unit speeds (e.g. WLAN)
- More complex than some alternatives (c.f. 802.11a vs 802.11b)

Diversity

- Diversity: the provision of two or more *uncorrelated* (independent) fading paths between transmitter and receiver.
- Performance improvement results as it is unlikely that all the diversity paths will be poor at the same time. Consequently, the probability of *outage* is reduced.
- Methods for generating uncorrelated paths for diversity combining include time, frequency, polarisation, angle, and space diversity.



(i) Space Diversity



(ii) Power Variation with Distance

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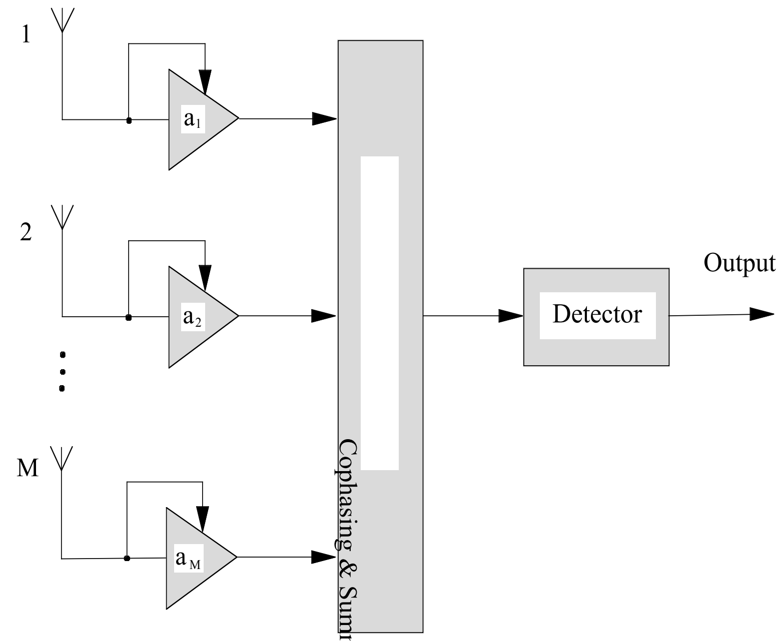
Diversity combining

- Switched combining: the current branch is used until a metric fails a certain threshold (e.g. Received Signal Strength Indicator)
  - Cheap and simple, but not ideal
- Selection combining: the most appropriate branch is always selected. Slight performance advantage over switch diversity.
  - All diversity branches must be analysed
  - RSSI is not ideal – unduly affected by interference
- Equal Gain Combining: simply co-phase and sum all branches
  - Multiple receive chains are required
- Maximal Ratio Combining: each branch is co-by its signal-to-noise ratio.
  - Optimal performance
  - Requires multiple receive chains and S/N calculation



MRC

(for EGC a_i=1)

Wireless technologies:
Spread Spectrum

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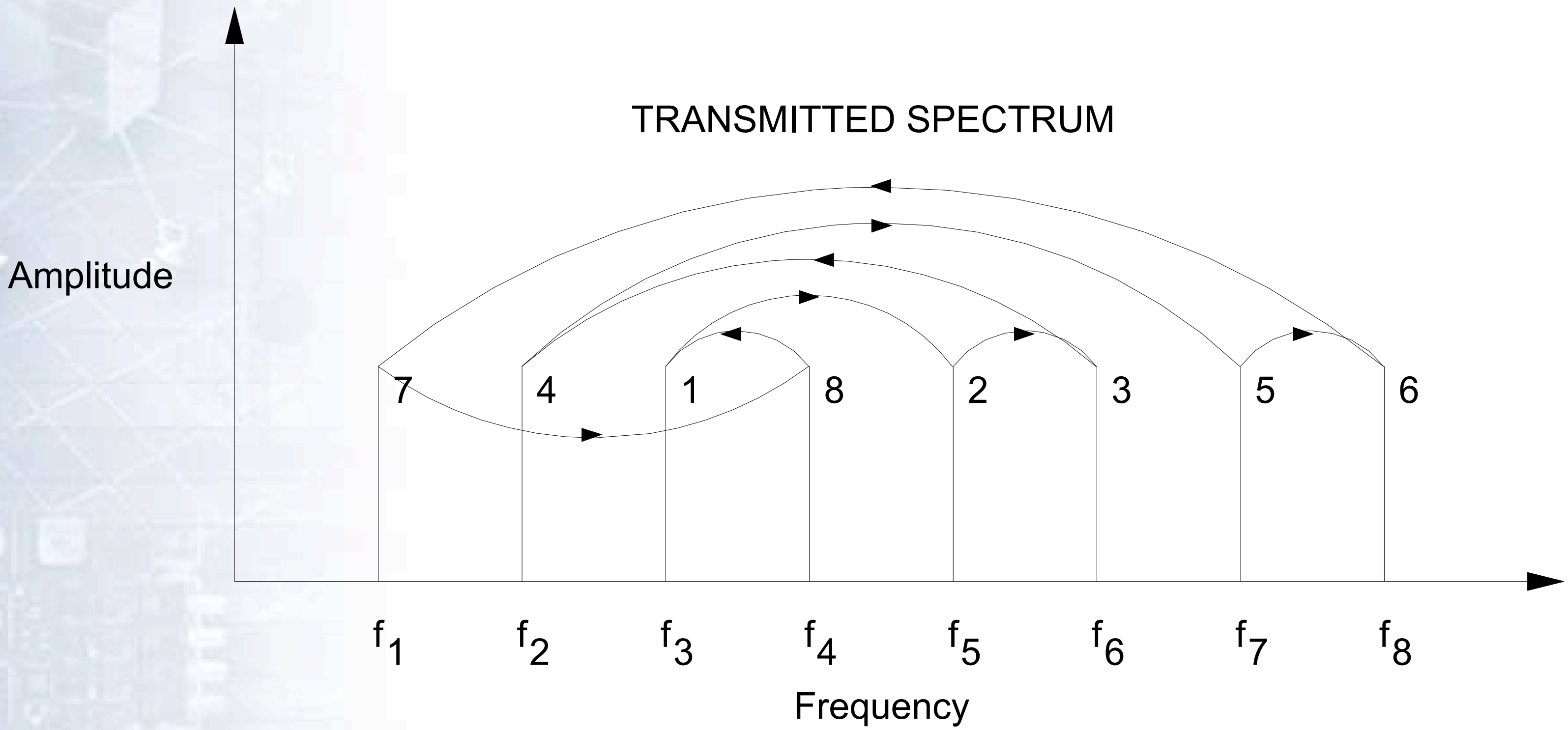
What is Spread Spectrum?

Classification of Spread Spectrum Systems: Frequency Hopping

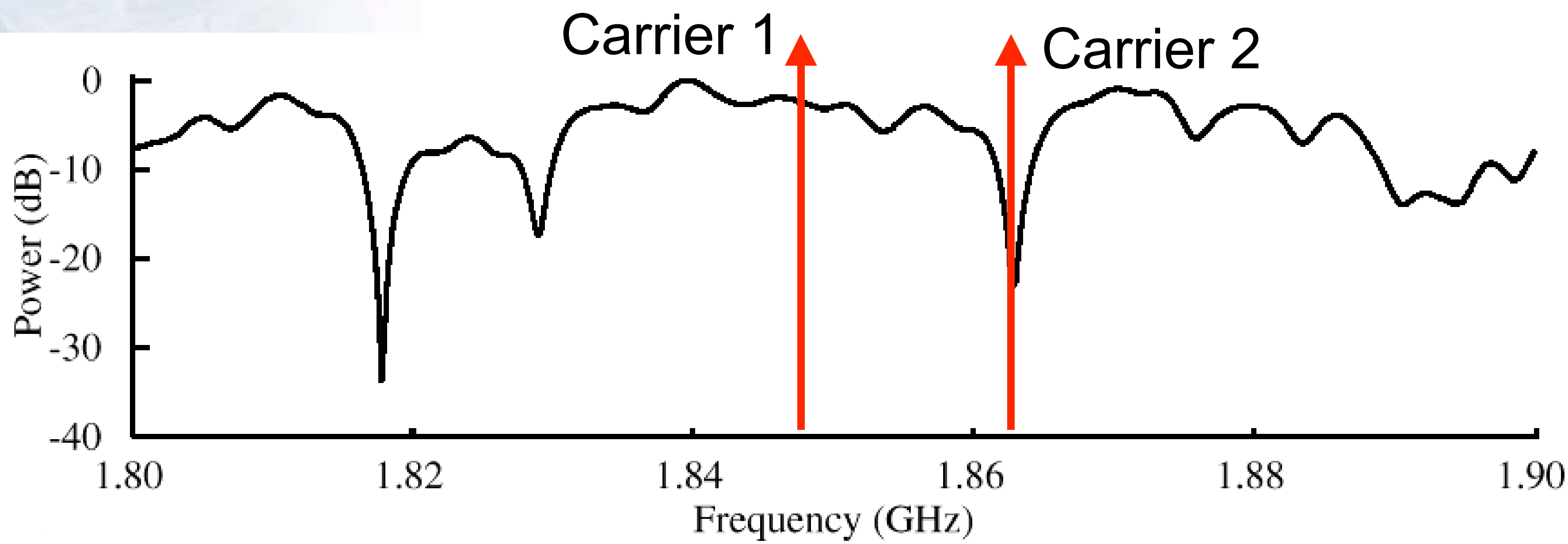
Frequency Hopping (FH)

- 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

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

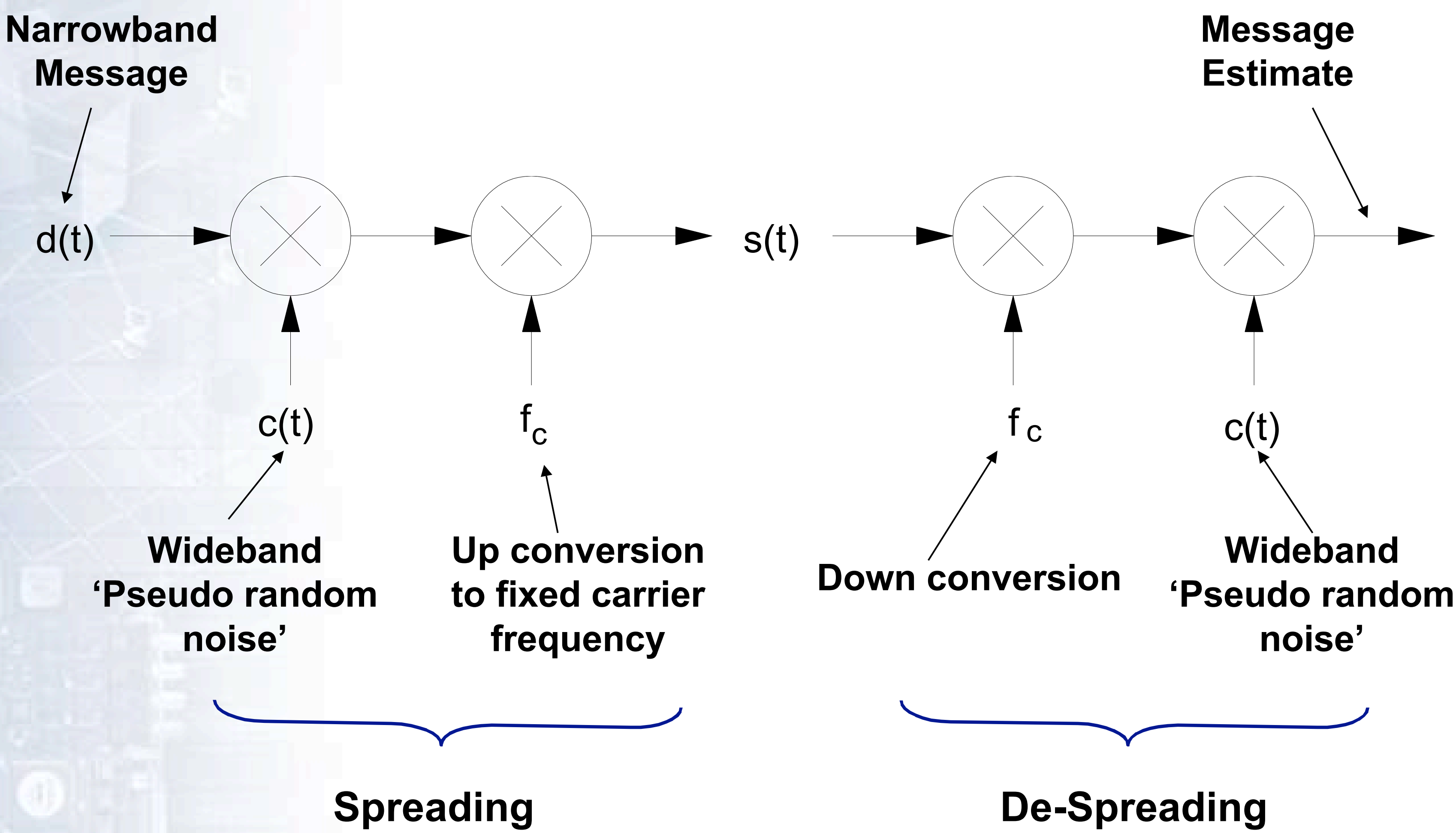
- Bluetooth Wireless Personal Area Network.
  - Robust to interference (ISM band).
  - Maximise likelihood of successful retransmissions.
  - 1,600 hops/second.
  - Based on IEEE 802.11 WLAN specifications.
- Frequency Hopped Spread Spectrum is a candidate system for Wireless Local Loop.
- The GSM specification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

Classification of Spread Spectrum Systems: Direct Sequence (DS)

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.

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

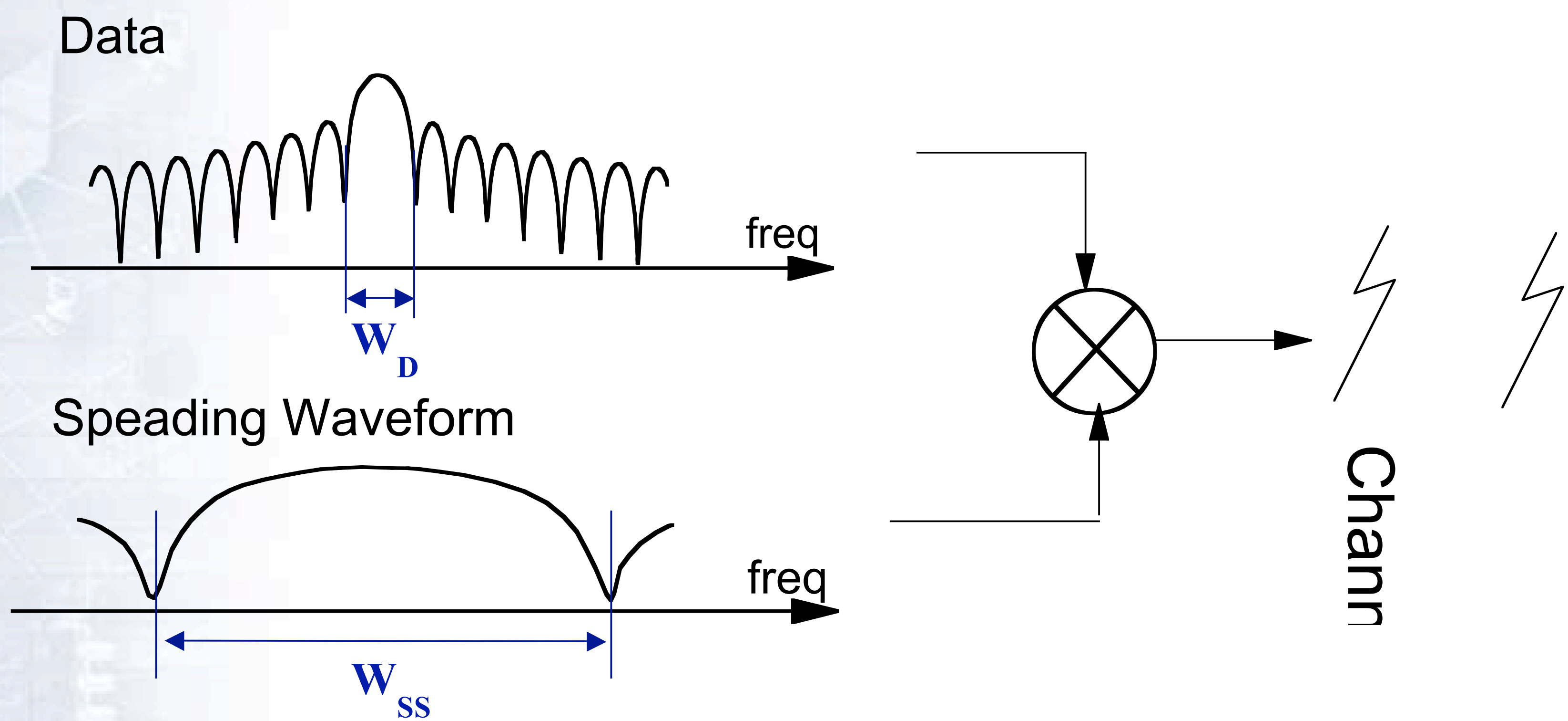
Spreading Codes

- 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

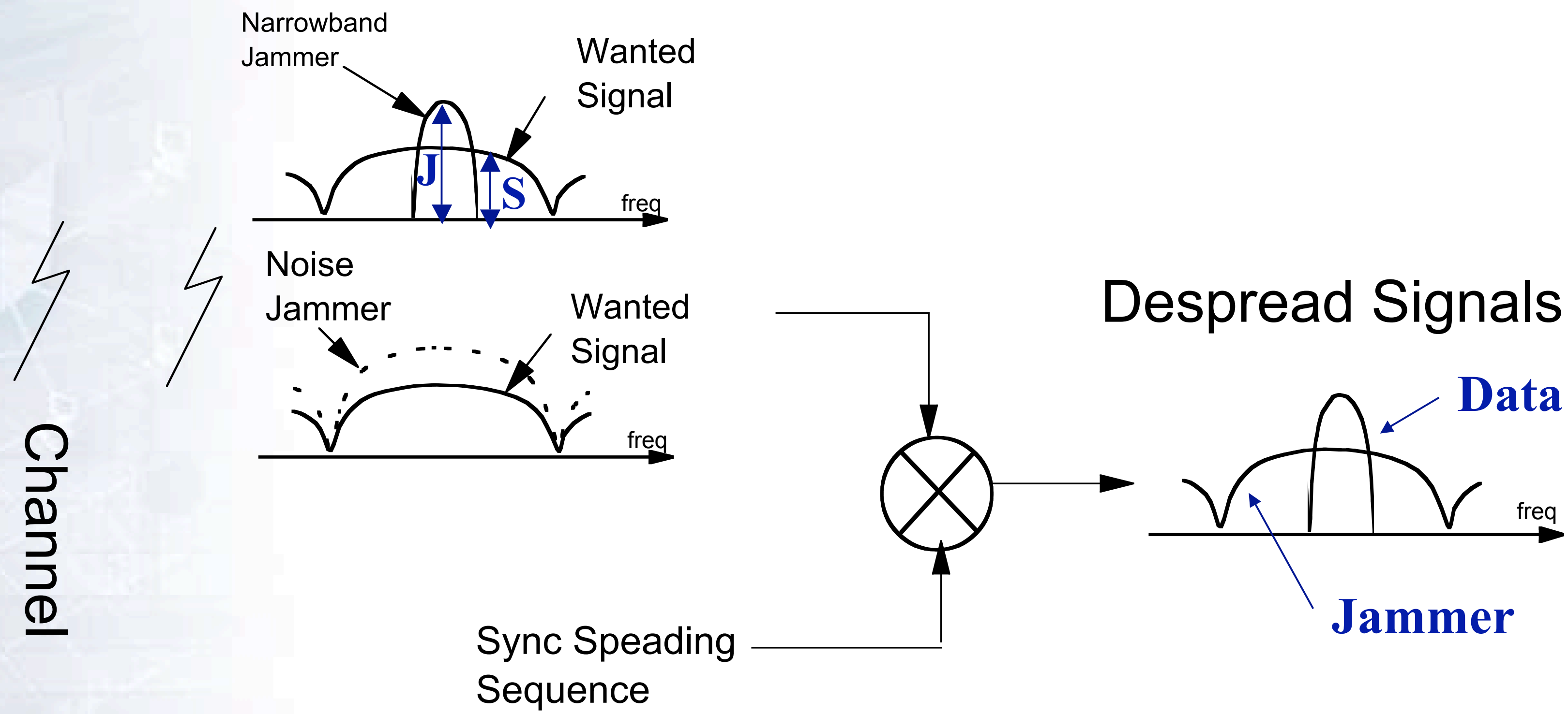
- Walsh and Hadamard sequences
  - zero correlation between codes when aligned
  - cross-correlation non-zero when time shifted
  - fixed spreading factor (codes of different length are not orthogonal)
- Orthogonal Variable Spreading Factor (OVSF) codes
  - permit orthogonal codes for different rate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

Processing Gain in Direct Sequence



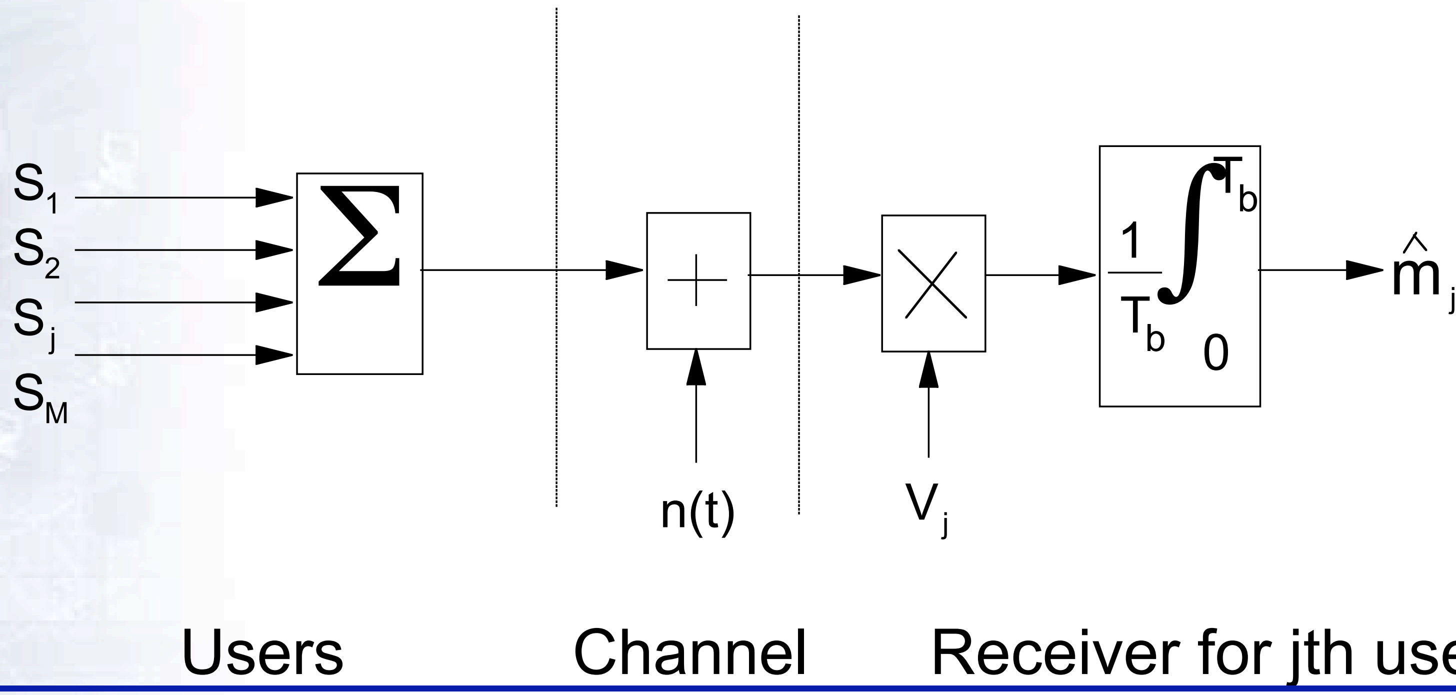
Processing Gain, PG $= \dfrac{W_{SS}}{W_D} = \dfrac{R_C}{R_D} = \dfrac{T_D}{T_C}$

Processing Gain in Direct Sequence



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

Multi-User DS/SS System - CDMA



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

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

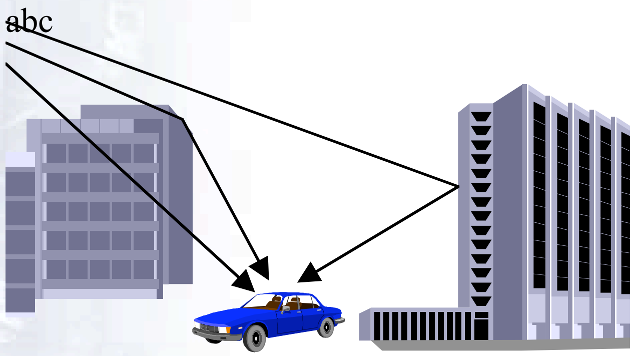
$$M = PG\left(\left(\frac{N_0'}{E_b}\right)_M - \frac{N_0}{E_b}\right)$$

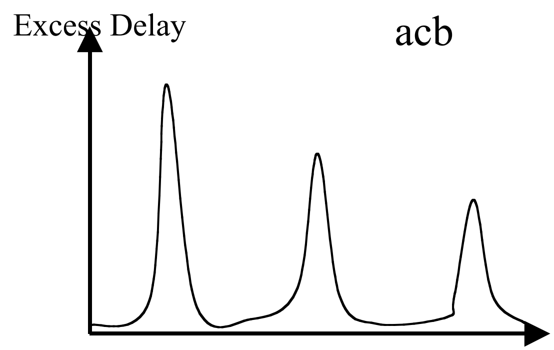
$$\text{Bandwidth Efficiency} \propto 1\Big/\left(E_b/N_0'\right)$$

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

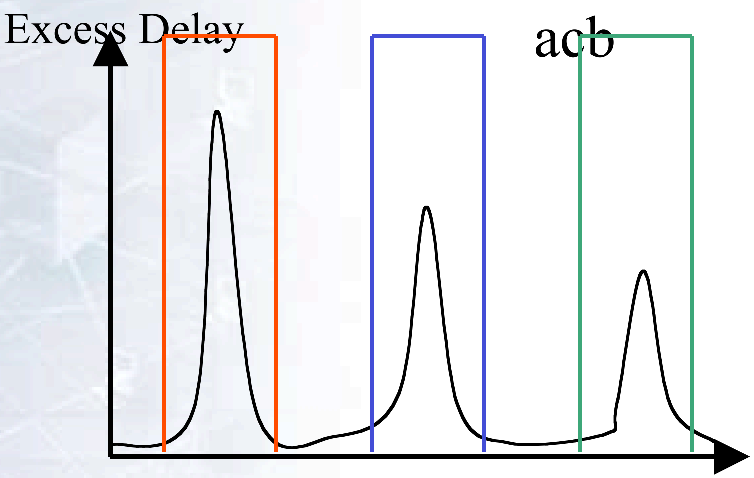
The Multipath Environment





- 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.

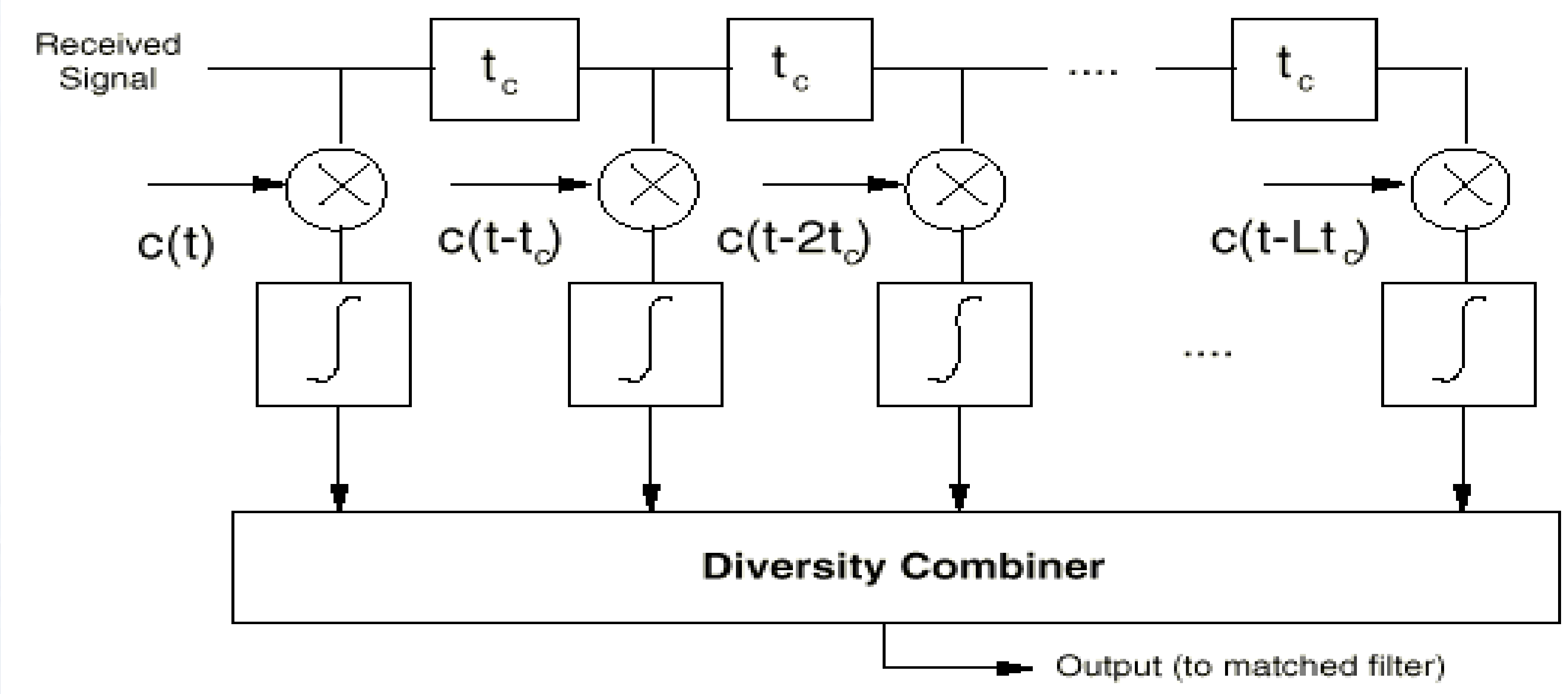
Path diversity in the multipath environment



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

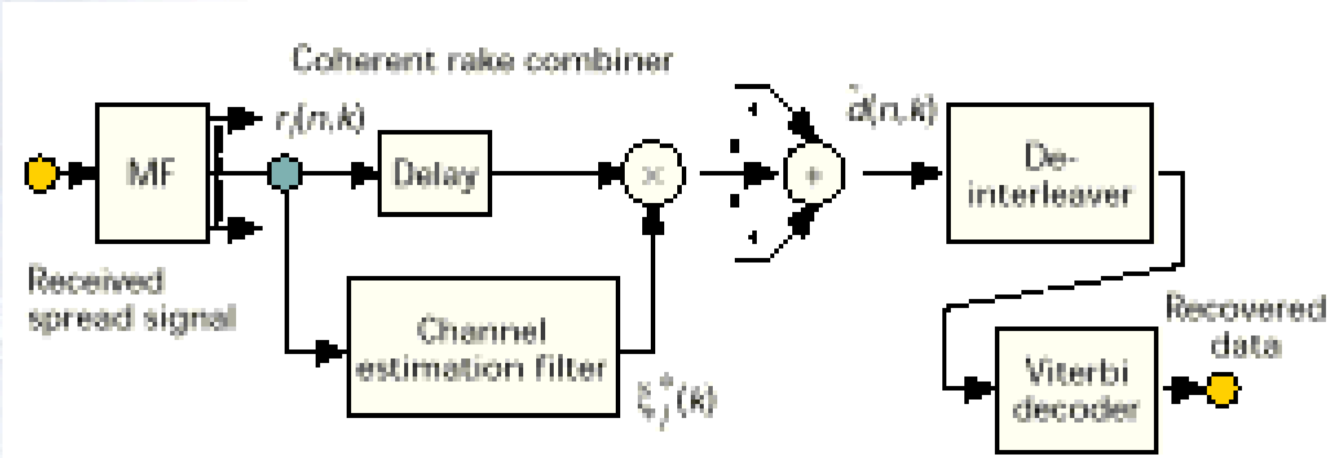
- Path diversity can be exploited by separating out the multipath components, co-phasing and summing them.
- Number of paths resolved (Lm) depends on the total multipath delay (Tm) and the chip period (Tc)

RAKE receiver



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

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

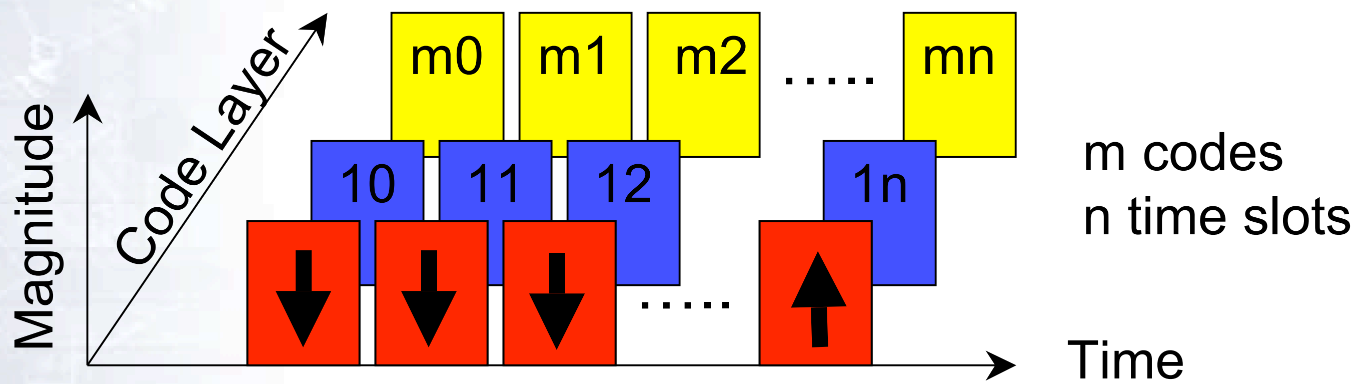
W-CDMA in UMTS

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 Spread Spectrum
  - 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 Spread Spectrum
  - Suitable for ad hoc networks (no near-far problem), e.g. Wireless PAN
  - Robust to interference
  - Limited data rate
- Both can provide multiple access (CDMA)
- Possible to combine with OFDM?

Why do I need to know how my radio works? Back to our first questions

Q: What's the difference between WiFi modes – is 802.11a better than 802.11b?

A: 802.11a uses OFDM and therefore can achieve a higher data rate

Q: Bluetooth is cheap, why can't I use it for everything?

A: Bluetooth is good for short-range, cable replacement. Data rate, range, and services might be limited

Q: Why is my wireless link giving me poor performance? Can I just increase the transmit power to improve things?

A: It could be noise, interference or the effects of the wireless channel. Increasing transmit power may not solve the problem, e.g. diversity might be appropriate to combat the wireless channel

Q: What can we expect from the future of wireless communications? Will it provide ubiquitous, pervasive connectivity?

A: Multiple-Input Multiple-Output techniques, Ultrawideband, Multicarrier CDMA, ad hoc mesh networks, and…?

Thank you

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