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What's so great about Digital Radio anyway?

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Research & Development
BRITISH BROADCASTING CORPORATION

BBC Research & Development
White Paper WHP 107

What's so great about Digital Radio anyway?

Abstract

This White Paper presents the slides and notes used for the series of IEE Section Lectures given by Mike Ellis during 2004 to introduce DAB Digital Radio. The presentation was given in Norwich, Guildford, Southampton and Cambridge to audiences comprising mainly current and retired engineers, but with a number of non-technical people also present. It is therefore a balance of technical and consumer information, and hopefully contains something useful and interesting to most people.

Keywords: DAB; Digital Radio; OFDM; COFDM; FEC; MPEG; DTT; WiFi; DVB

White Papers are distributed freely on request.

Authorisation of the Chief Scientist is required for publication.

Slide 1

DAB Digital Audio Broadcasting

What's so great about Digital Radio anyway?

Mike Ellis, BBC Research and Development

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Research & Development BBC

Slide 2

About BBC R&D

Research & Development BBC

Located at Kingswood in Surrey

Approximately 200 staff

Many different areas of expertise

Lots of gifted engineers, many destined to be high fliers

Approximately 120 Engineers

Analogue systems (AM; FM; PAL; …)
Digital systems (DAB; DTT; …)
“Fundamentals” (sound; pictures; radio channels; …)

Slide 3

One of the high fliers

Attended the University of Kent at Canterbury reading Electronic Engineering obtaining a first class honours degree in 1993

First job: designing a band-pass filter

Current job: replacing the entire DAB system

Along the way:

- Worked on the design of a high efficiency power amplifier for use at DAB transmitter sites
- Developed a technique to allow the output from a DAB transmitter to be analysed to ensure it complies with the spectrum mask – very high dynamic range required
- Developed the technique to allow the entire transmitter network to remain synchronised
- Developed the equipment to get the DAB signal from Broadcasting House to each of the transmitter sites
- Investigated the possibilities of using digital pre-correctors to boost the efficiency and/or power handling of the DAB transmitter
- Re-written the multiplexing software to support many of the extra features present in DAB
- Designed and coded much of the control system for the DAB systems in Broadcasting House
- Developed a receiver testing schedule to ensure that commercial products comply with the specifications
- Developed a DAB testing strategy to ensure that the transmission equipment complies with the specifications

Slide 4

About this talk

- Why was DAB developed?
- How does DAB work?
- How did the BBC implement DAB?
- Other similar systems

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Slide 5

Why was DAB developed?

Why spend all that money?

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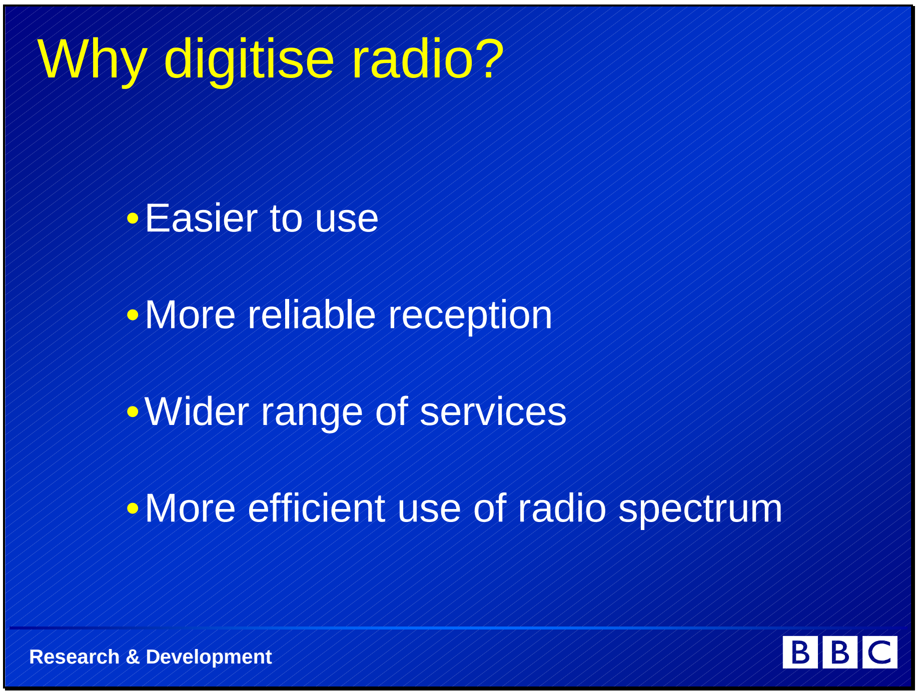
Slide 6



1. Many people were “scared” to adjust the tuning on their radio in case they couldn’t find their favourite station again.
2. Both FM and AM are affected to some degree by the weather and nearby objects.
3. Existing radio services were only capable of carrying sound – sometimes not even stereo.
4. A single national FM service requires 2MHz of spectrum to be allocated to it, even though each individual transmitter only requires 150kHz.

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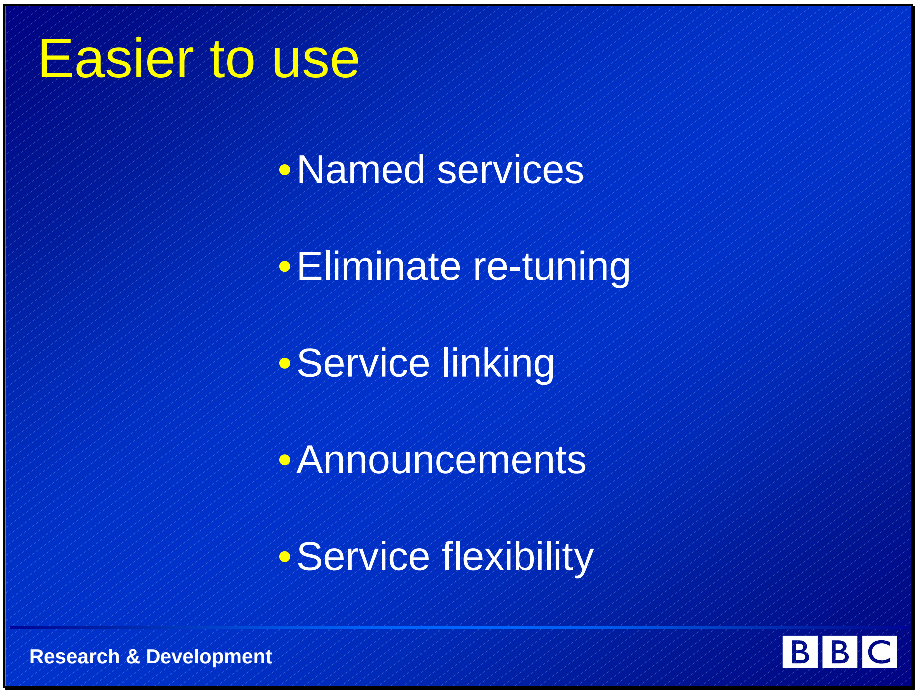


RDS was developed in the 1980's as a "bolt-on" enhancement to FM to address some of the shortcomings

1. RDS does this for FM – albeit only short, eight character names – DAB offers names at least sixteen characters long, which means "BBC LDN" can grow back the vowels (and consonant)!

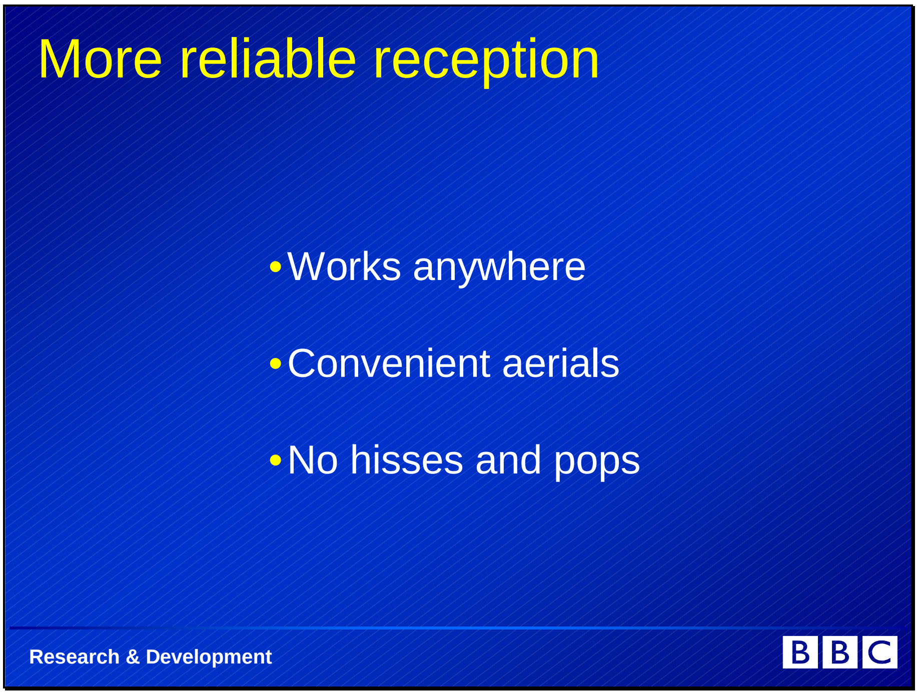
2. RDS automates re-tuning for FM – but this results in the receiver "muting" while it checks another frequency (or having two front ends – and very few do!) Much better to eliminate the retuning completely - and this could also release spectrum.

3. Handover between local or regional services carrying similar content

4. RDS has support for traffic announcements, but that's all. DAB adds many more, e.g. headlines, sport-flash, weather report

5. Part-time services to cover special events without "hi-jacking" existing stations – flexible allocation of the bits allows "stealing" a little bit from lots of services to "make room for" additional services, perhaps to cover many football matches on a busy Saturday afternoon.

Slide 8



1. In the kitchen, in the car, in the office, in the park. Car probably the worst environment – lots of reflections (multipath) AND lots of Doppler error (fast moving – DAB was invented BEFORE the London Orbital Roadworks!!!)

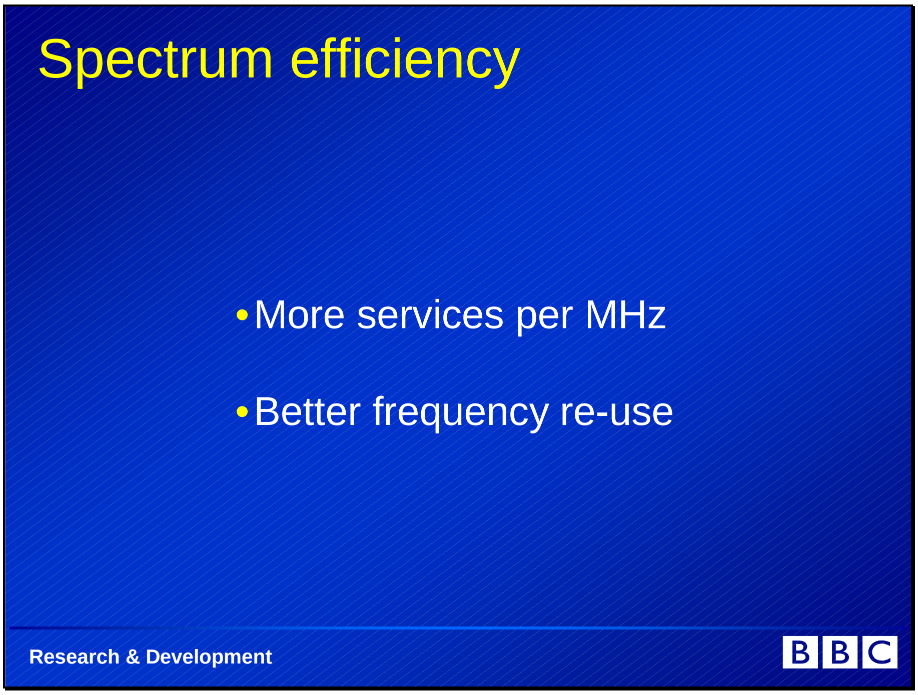
2. Small, flexible, preferably internal

3. The car at traffic lights problem…move forwards 10cm and go from almost nothing to perfect reception – or vice versa!

Slide 9

1. Information about the current track being played, or the telephone number and question for the phone-in quiz, adverts – the list goes on and on.
2. Why limit ourselves to text? Why not have still pictures, or even short animations or video clips such as you might find on the World Wide Web
3. With all these distractions, perhaps you just missed the start of the Archers on Radio 4 – wouldn't it be good if you could just wind the radio back by a few minutes?
4. Lots of extra services means it's even more important to know what is on, and when. Let's use some of the data to carry the "Radio Times".

Slide 10



FM uses 88-108MHz, 20MHz of spectrum. We get six national services, plus a handful of local and regional services. Each national services requires 2.2MHz of spectrum because each transmitter must be on a different frequency to its neighbours – thus we can only re-use a single frequency a few times across the country – a bit like the four-colour theorum for cartographers, but with the added problem that the edges of the areas are a bit blurred.

By comparison, DAB uses 13MHz of spectrum from 217-230MHz (in the UK – other countries have different allocations) to carry 7 multiplexes. A single DAB multiplex carries up to 10 services (a mixture of stereo and mono, music and speech) yet only occupies 1·5MHz – this would take 22MHz with FM, so you can argue that DAB is nearly 15 times more efficient.

In fact, of the seven frequencies allocated in the UK, only two are allocated for national multiplexes (groups of services), giving around 20 simultaneous national services. The other five frequencies are allocated for regional and local uses. Around London, we now have five multiplexes which can be received, and over 60 services are available, some of them only part-time services.

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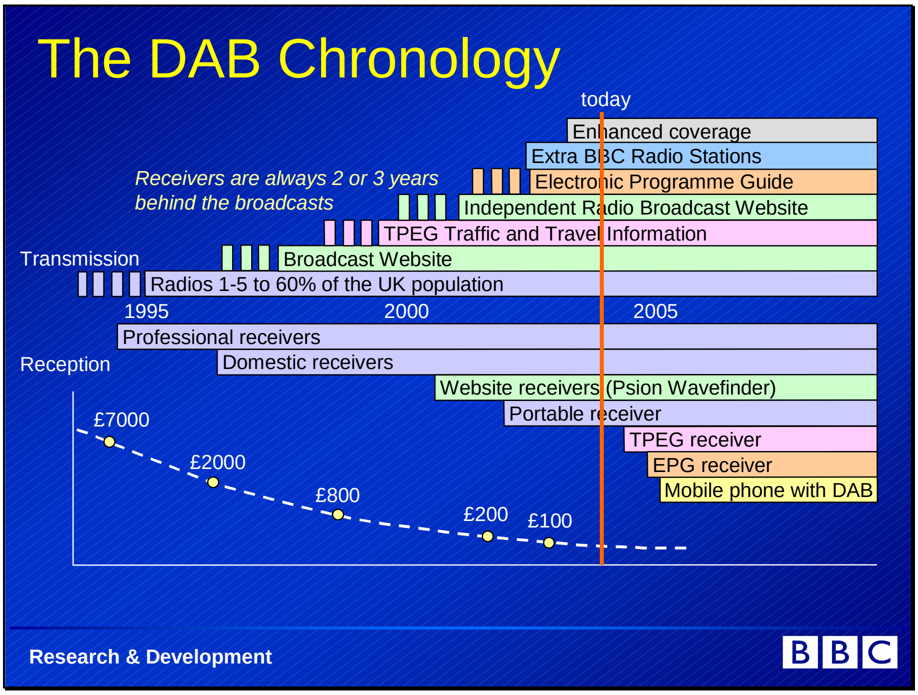

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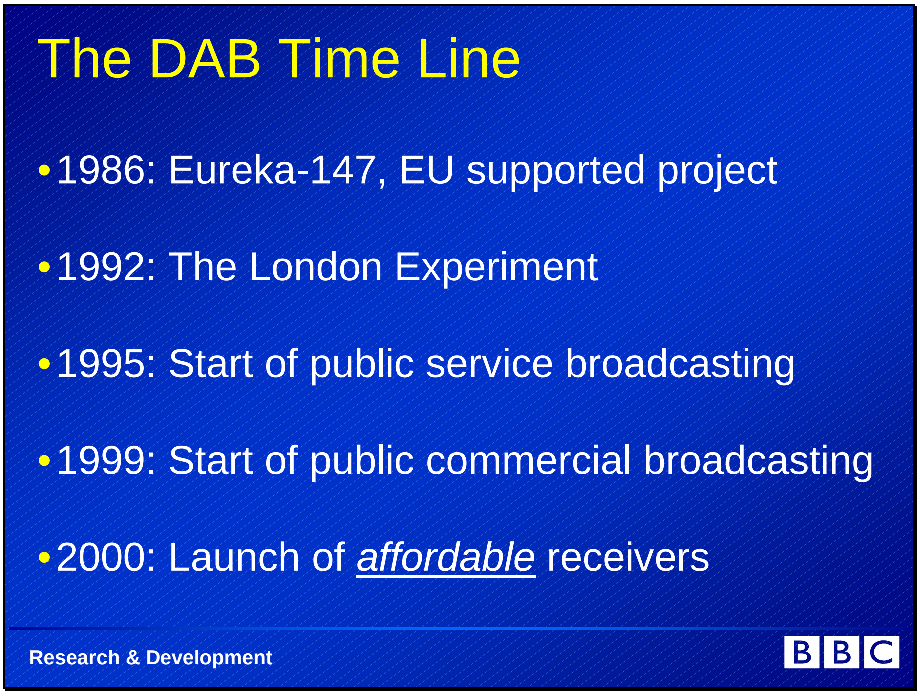

Eu-147 – the original name for DAB!

London Experiment - initially four transmitters around London, manually synchronised (ish!!!) later extended to five transmitters. Intended to prove that DAB could be made to work outside the lab.

Public service broadcasting – BBC and Swedish Radio both commenced broadcasts “for real” on the same date – 27th September 1995. Test transmissions had been going on earlier, however since that date there has been no time during which the UK network hasn’t been broadcasting.

Slide 13

Receiver models

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Receiver models

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Receiver models

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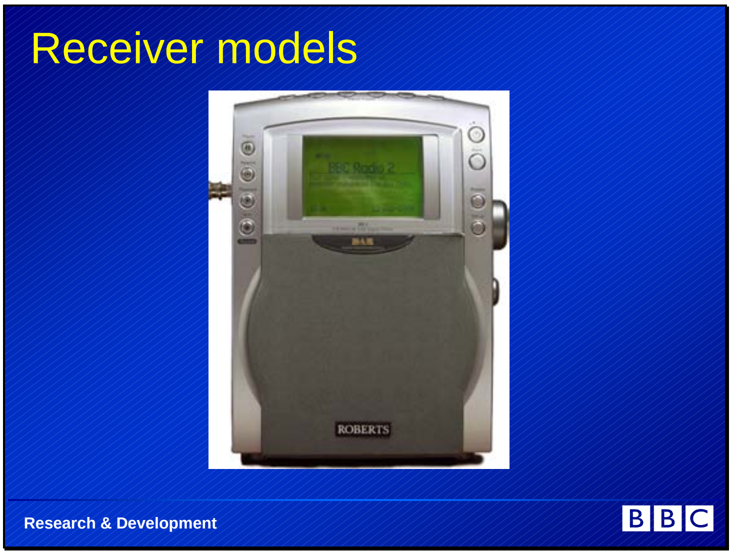
Slide 13


Receiver models
ROBERTS
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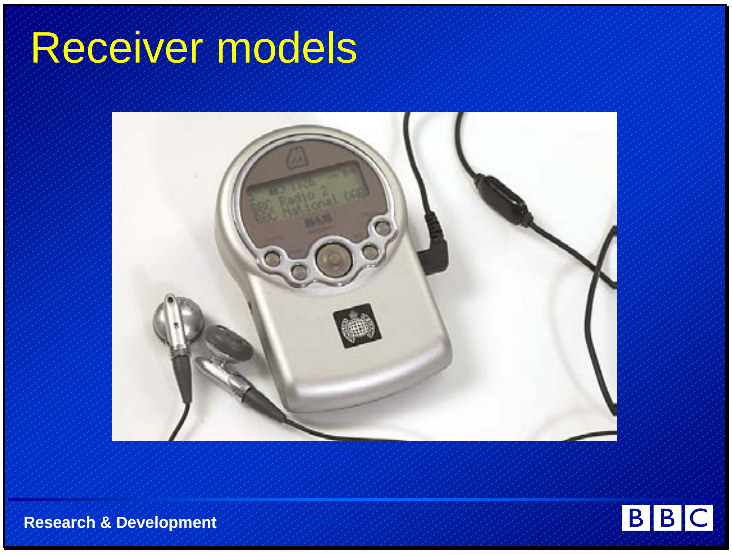
Receiver models
Research & Development
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Receiver models
Research & Development
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Slide 14

How does DAB work?

Very well indeed, thank you!

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Slide 15

How does DAB work?

- COFDM
- Multiplexing
- Audio Bitrate Reduction

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DAB uses multiple technologies to address the challenges it faced.

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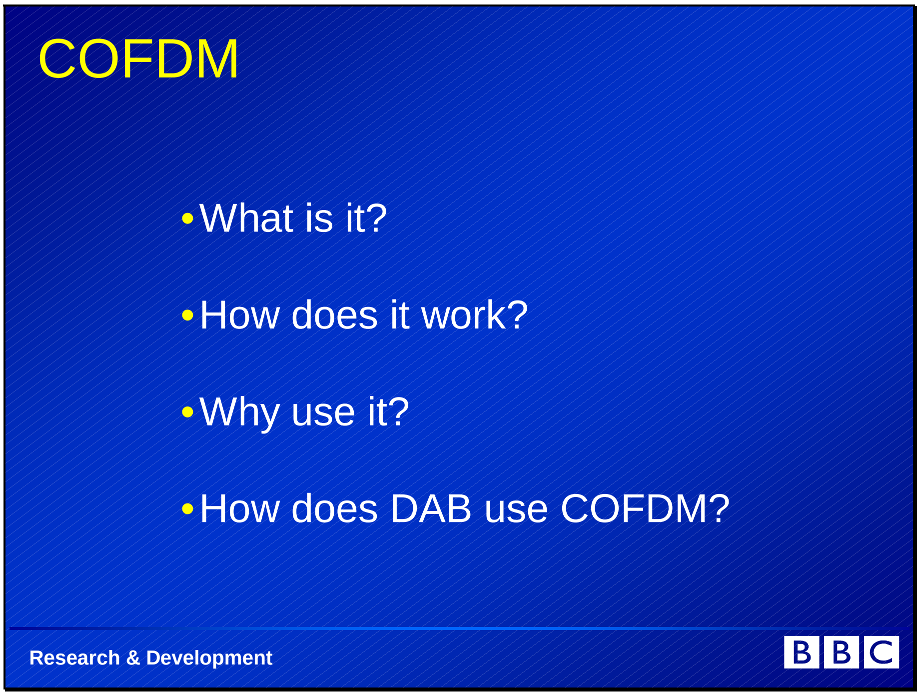

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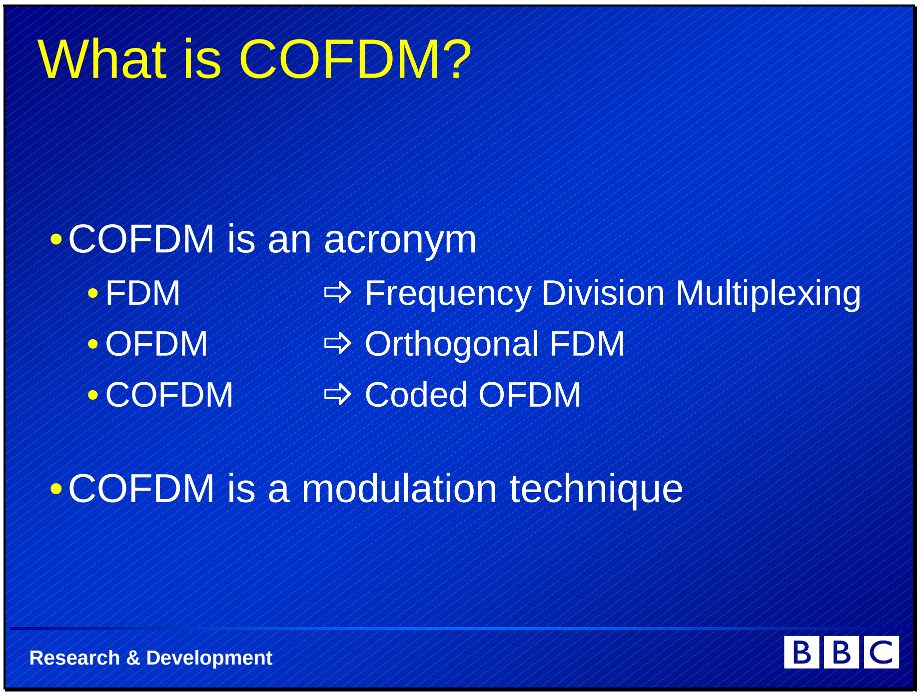
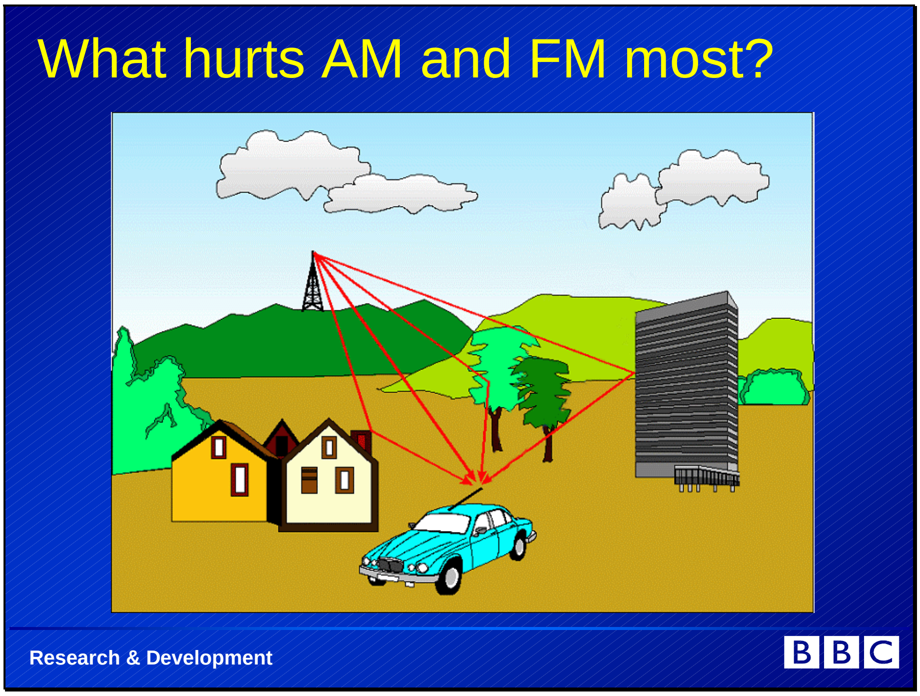


FDM – dividing data across a number of different frequencies. Even if one frequency is poorly received (e.g. fades), (some) other carriers will be unaffected. The further apart the frequencies are, the more likely it is that poor reception will be "localised".

Orthogonal – exploits the characteristics of a modulated carrier to ensure that no carrier is directly affected by any other

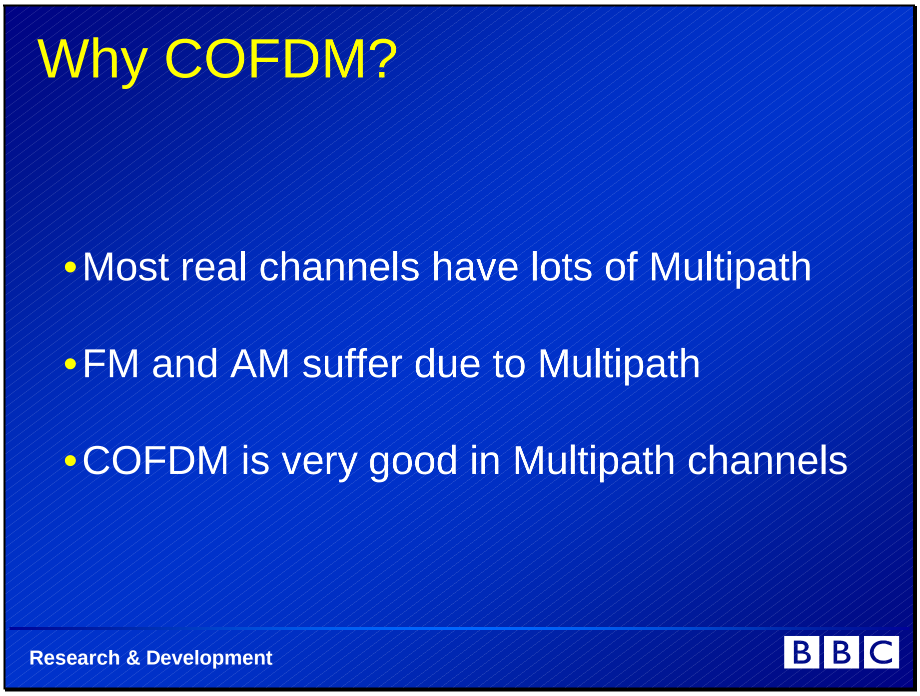
Coded – uses Forward Error Correction to reduce the bit error rate of the raw system

Slide 18



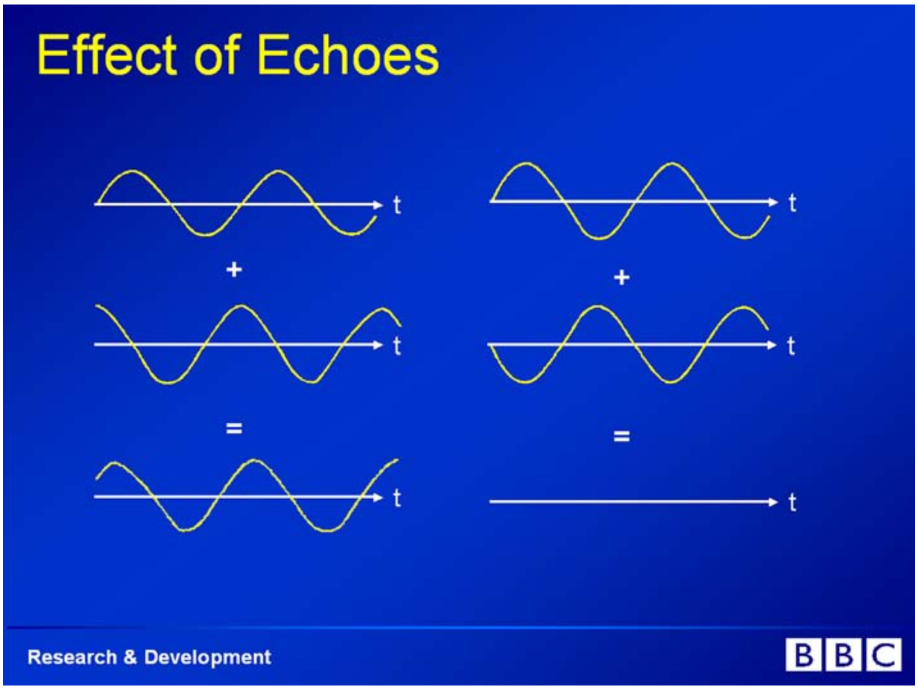
In many ways, Multipath is a fancy word for Echoes!

Slide 19



OK – so that's why – but how does COFDM work so well with a multipath channel

Slide 20



First things first – why exactly are echoes such bad news for AM or FM?

Add one sine wave to a delayed version of itself and you get…. Another sine wave! The phase and amplitude may change – indeed in the worst case the two sine waves may cancel out exactly – however the exact delay require to cause two sine waves to cancel out depends on the frequency – slight up, or slightly down, and they won't cancel exactly.

Even better, the delay on a real channel actually changes fairly slowly, so if you received the carrier during one symbol, it is highly likely that you will be able to observe how it changes during the next symbol, and the CHANGE from one symbol to the next isn't affected by the summing process – if the transmitted signal shifts phase by 37 degrees or increases by 2dB, the received sum of echoes will also shift by roughly 37 degrees or increase by approximately 2 dB, provided that the delay is (at least approximately) constant.

The exact way that two signals combine depends on many factors: how far away is the object causing the echo, and in which direction; how reflective is the surface, and what frequency is the signal. Most of these we don't have much control over – but we DO have at least some control over the frequency we transmit on.

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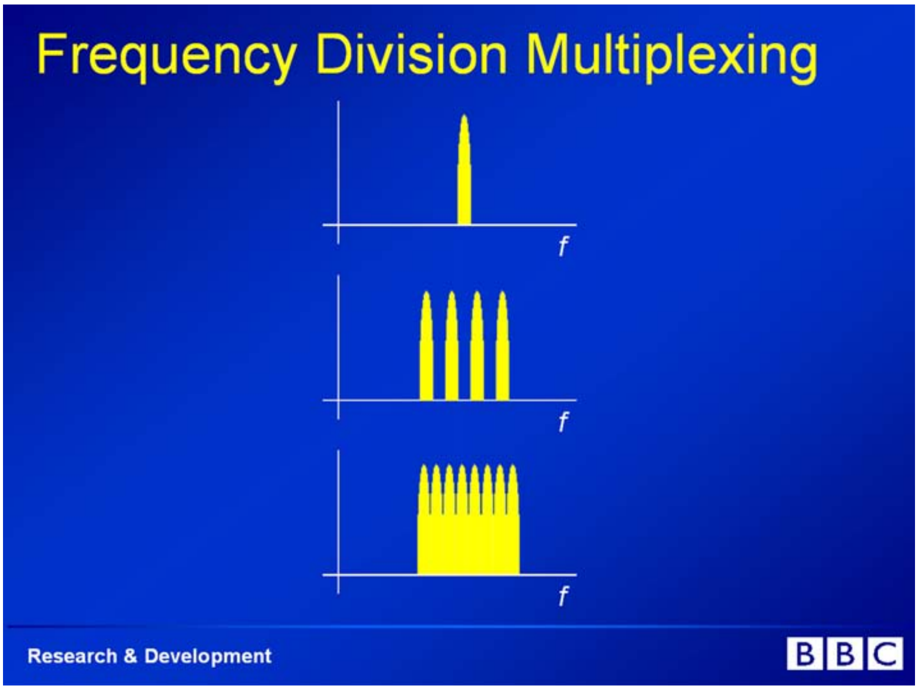
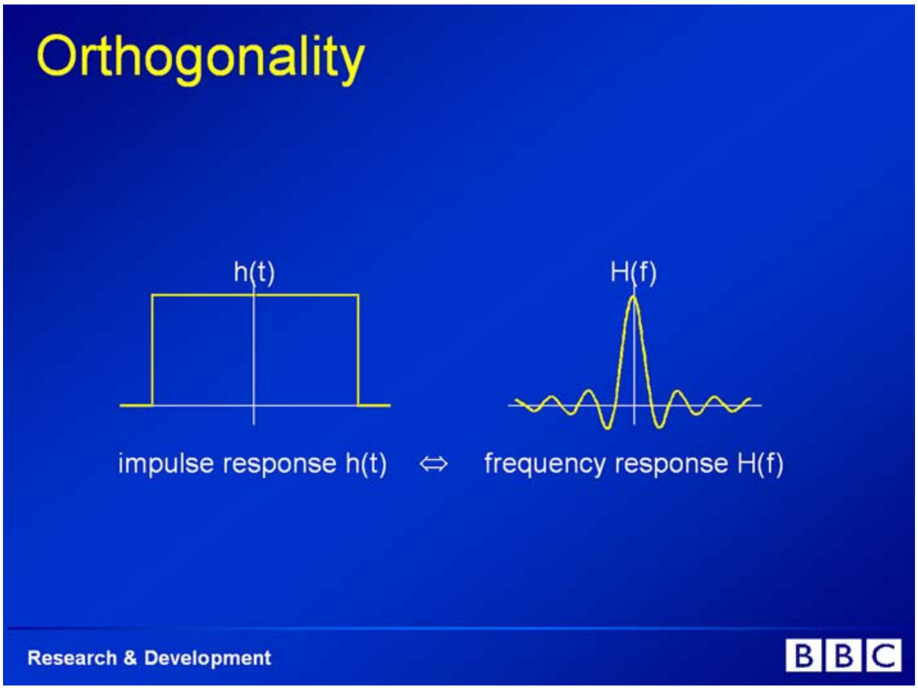


1. If we modulate a single carrier, we must modulate it fairly fast in order to carry any significant quantity of information. We also risk losing the data completely if we get an unfavourable echo.

2. If we split the data across a number of carriers, each carrier can be modulated more slowly, thus becomes closer to a pure sine-wave. Furthermore, if some of the carriers are destroyed (e.g. due to noise or echoes) there is still the possibility of receiving enough data from the carriers which remain to reconstruct the original data – I'll come back to this idea later on.

3. But… squeeze the carriers too close together and they start to interfere with each other

Slide 22



When you modulate a single carrier, it grows a series of “sidebands”. These sidebands extend to each side of the carrier nominal frequency following a sinc (sin-x over x) function.

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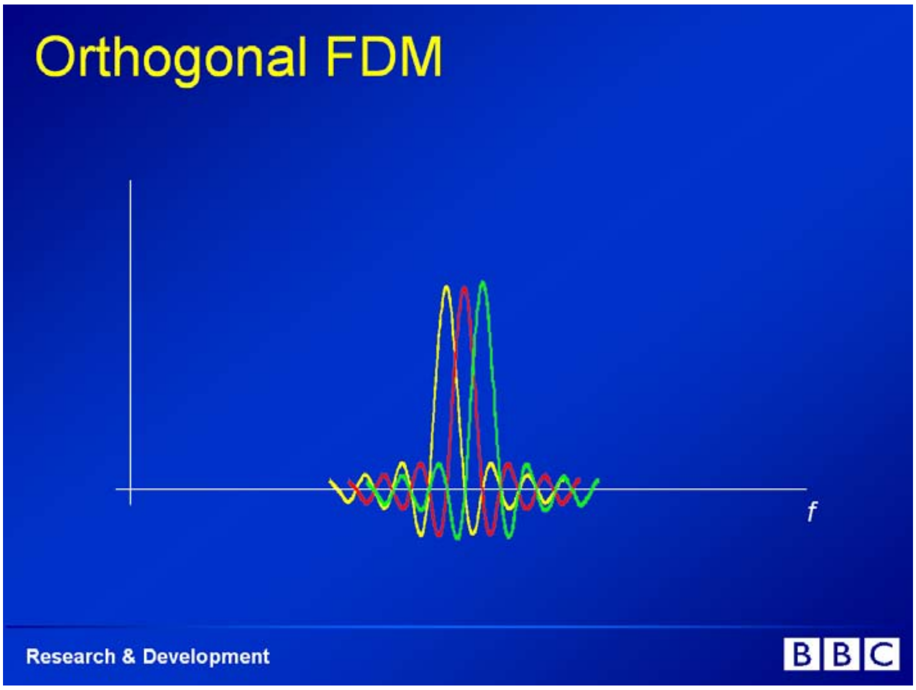
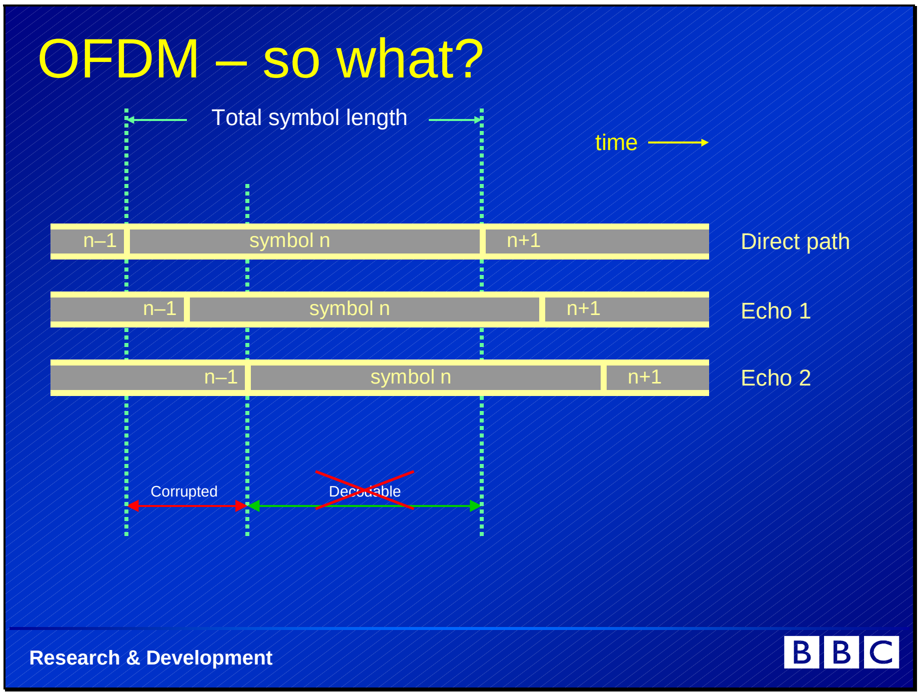


The clever bit with OFDM is that each carrier is contrived to exactly coincide with the modulation nulls for all the adjacent carriers. This is only possible by carefully controlling the carrier spacing and the modulation rate.

Although the diagram only shows three carriers here, the principal in theory extends for any number of carriers, and the DAB mode used in the UK employs 1536 carriers.

Slide 24

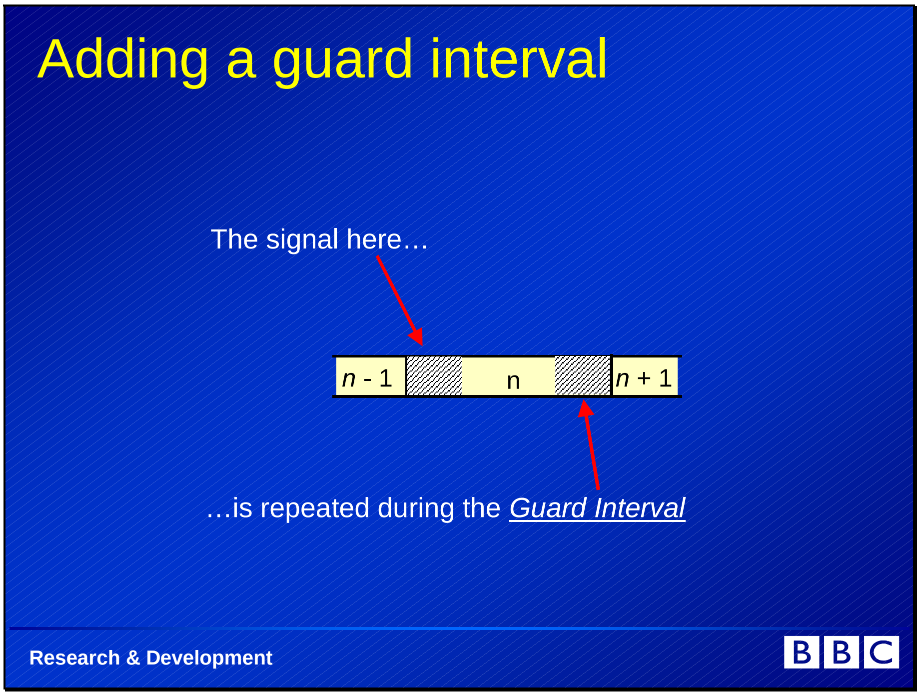


OFDM alone doesn't actually solve the echo problem. OFDM allows us to have lots and lots of carriers provided that we modulate them slowly. In fact, if we have enough carriers, we can modulate them very slowly. So slowly that the echoes are shorter than the modulation…

…but we still have a problem where the individual symbols overlap. Where different symbols overlap, we cannot decode the original data. Worse still, although you might think we can decode the portion where same symbol overlaps, in fact there is insufficient time left and even this portion is undecodable.

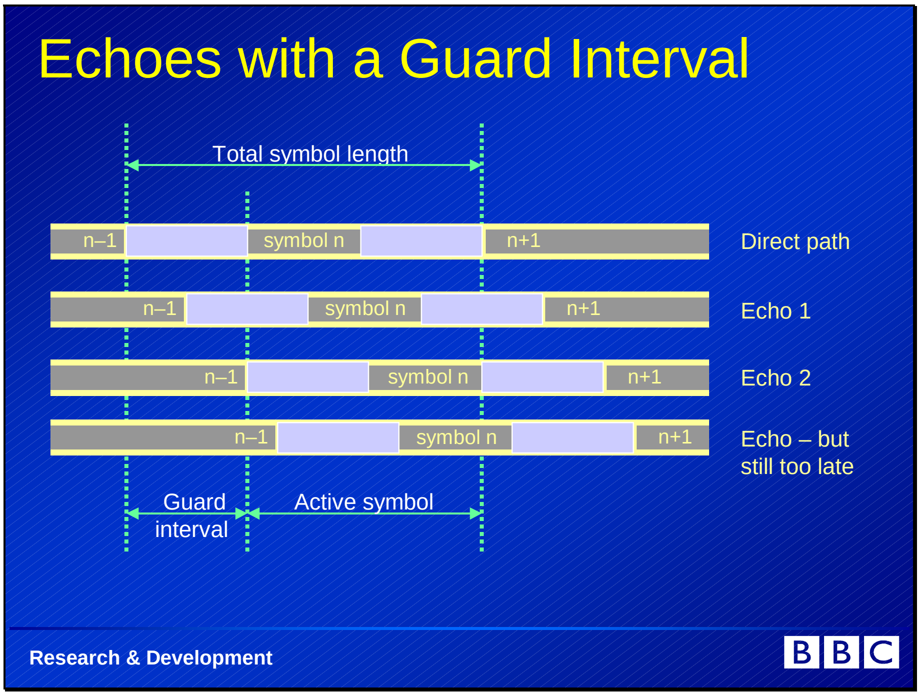
So is OFDM a busted flush?

Slide 25



Fortunately not quite – we can add a guard interval between symbols, and fill this period of time with a repeat of the beginning of the symbol.

Slide 26



Take a single signal…

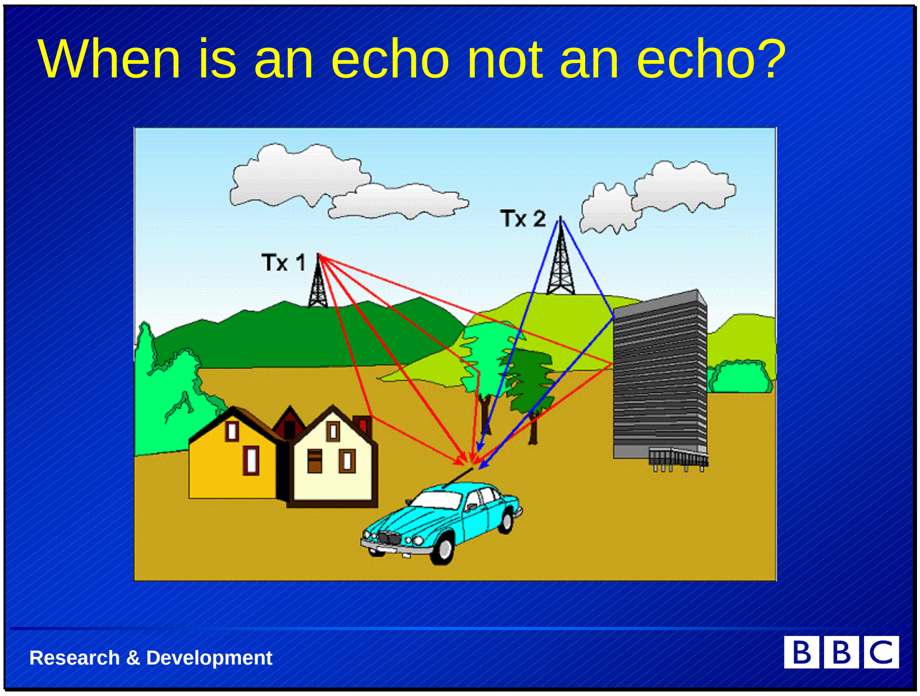
…repeat part of the signal to give us a guard interval

…which conventionally is placed at the start of the symbol

…then when echoes arrive, the guard interval means that we can still decode the entire active symbol

…unless an echo is "too late", when the data may be corrupted just as before

Slide 27



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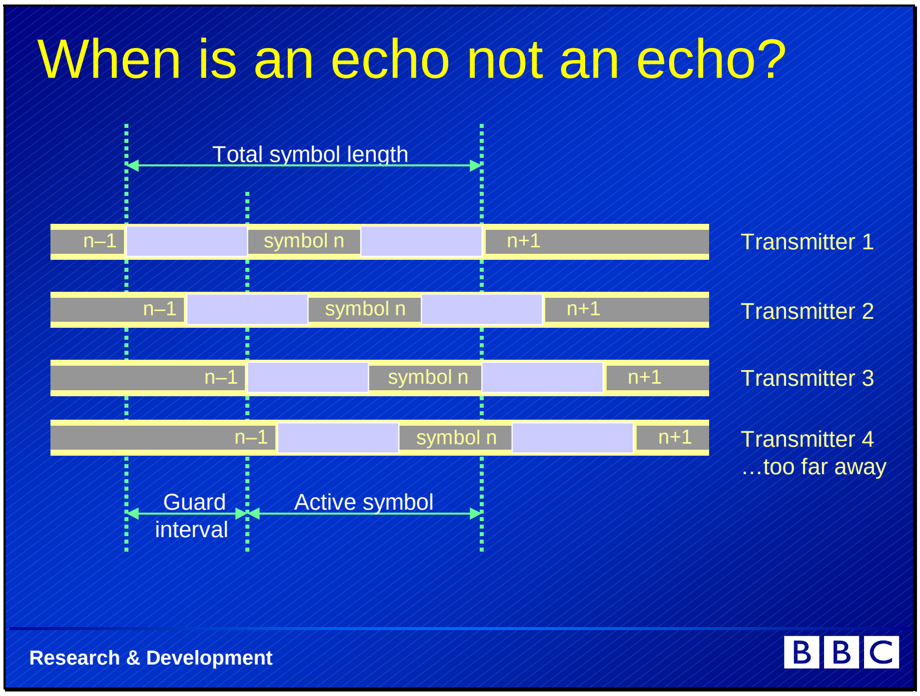
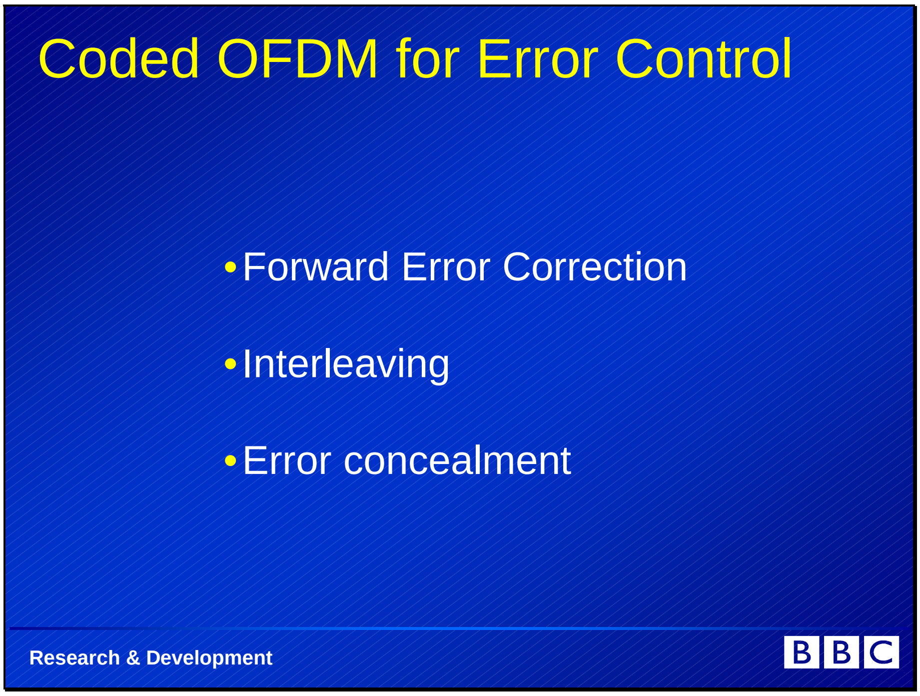


Well, an echo might not be from a building. It could perhaps be the same signal from a more distant transmitter. It is exactly the same thing to the receiver, and it is this ability to handle echoes which allows DAB to operate a Single Frequency Network across the entire of the UK, unlike FM networks which requires adjacent transmitters to be on different frequencies. This is one of the key features of DAB which makes the system more spectrum efficient than FM or AM networks.

Slide 29



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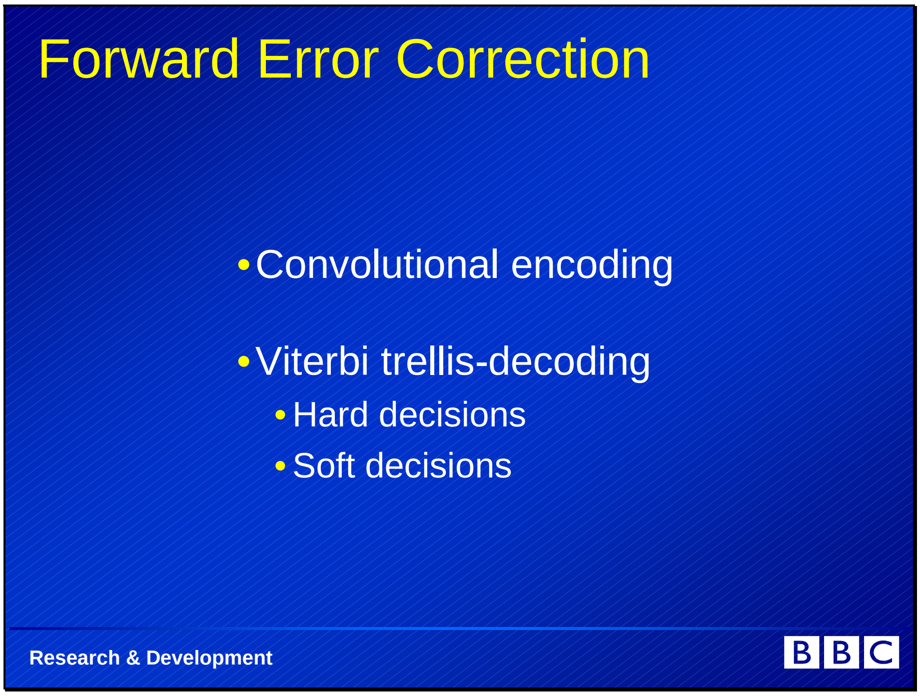
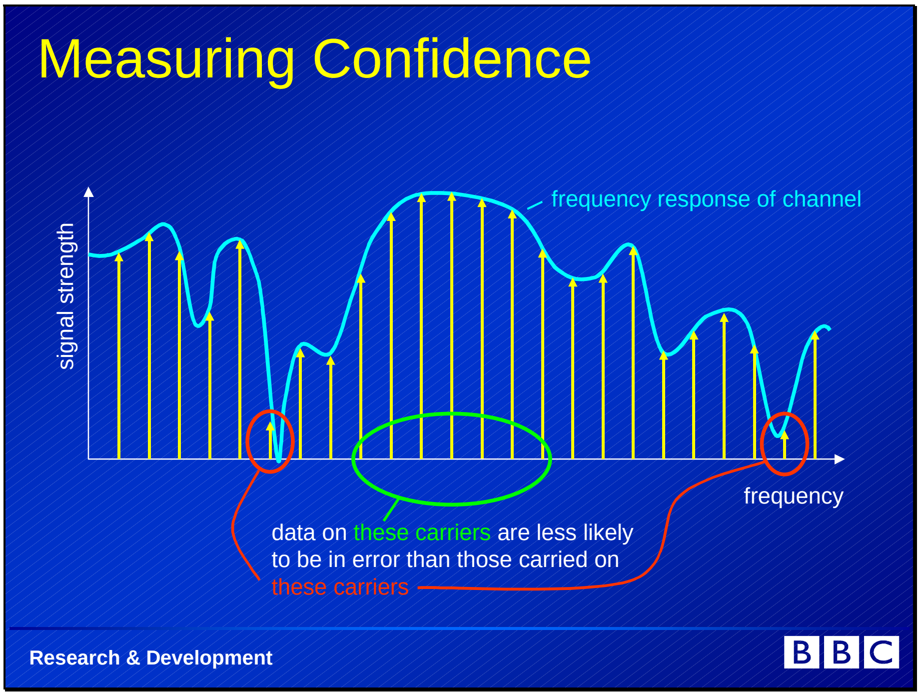


Forward Error Correction – transmitting more data than is needed such that when some is lost, what remains is sufficient to reconstruct the whole. Many people have heard of Reed-Solomon codes, however DAB actually uses a more powerful code still known as a Convolutional code. The basic premise remains unchanged, however.

Convolutional codes can be decoded in two ways. The simple implements hard decisions – each bit is treated on its own, as a one or a zero, and has no “shades of grey”.

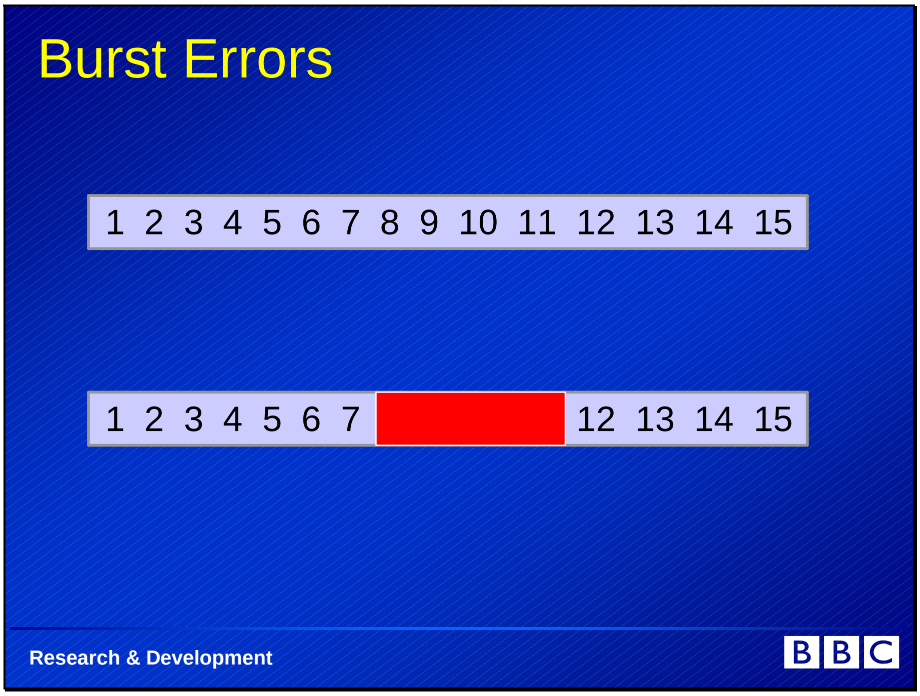
More advanced decoders use Soft Decisions, where the probability of each stage of the decoding is influenced by the confidence of the previous result. This increases the processing complexity in the receiver, but significantly improves the performance of the system as a whole.

Slide 31



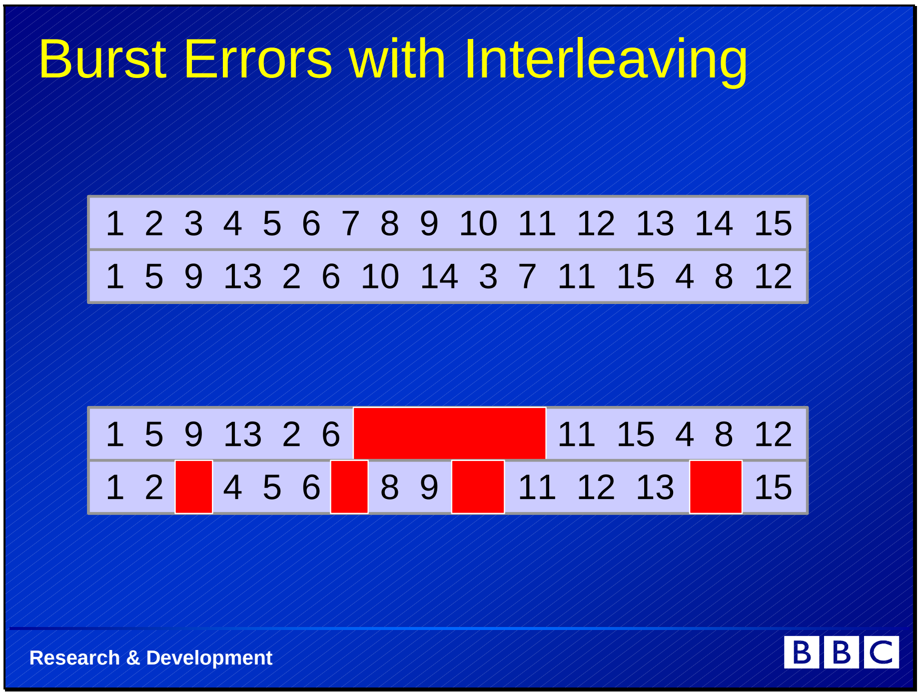
So what are these shades of grey? Well, imagine we receive a signal where some frequencies are adding together and others are cancelling out – like this.

Slide 32



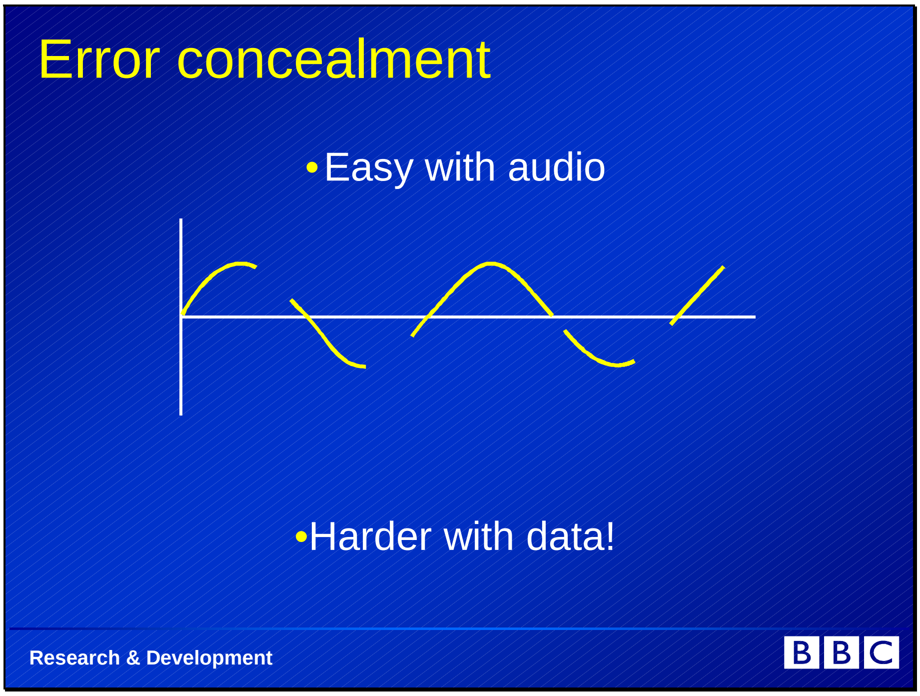
Forward error correcting codes tend to cope better with isolated errors rather than long bursts, while radio channels tend to give longer bursts of errors.

Slide 33



Forward error correcting codes tend to cope better with isolated errors rather than long bursts, while radio channels tend to give longer bursts of errors. Interleaving gives us a way to covert long bursts of errors into many isolated errors.

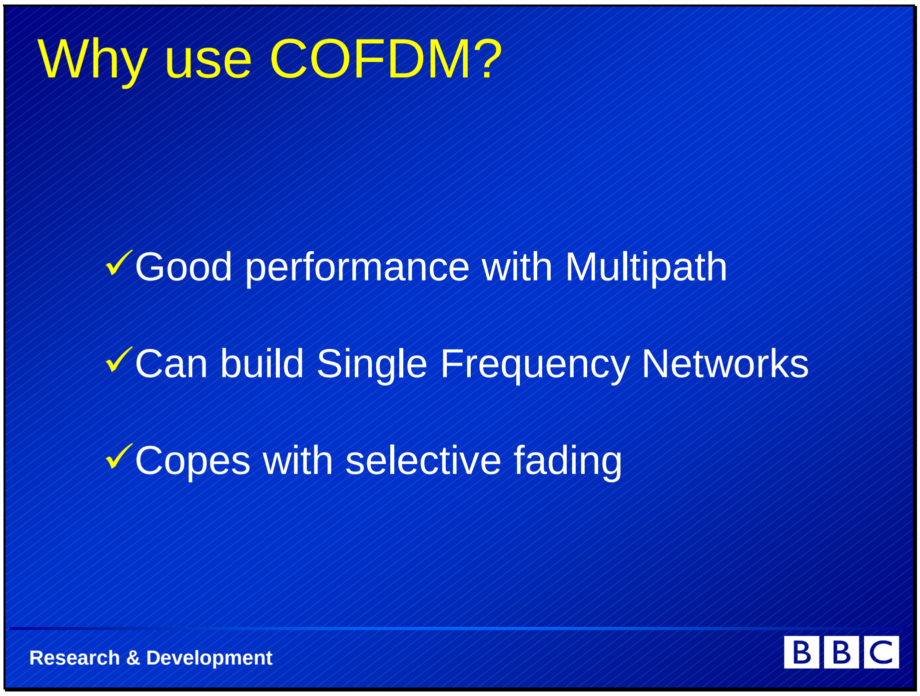
Slide 34



Audio is basically a continuous wave, so if we get gaps in it, we can usually predict what would have been in the gaps. Using harmonic techniques we can actually get an even better fit, so good that most of the time the human ear can't tell.

Data isn't predictable, so it isn't really possible with data in the same way as for audio. As a result, the Forward Error Correction applied to data must be much more powerful than the FEC applied to the audio, and we even use other techniques such as "carouselling" the data, that is, repeating the data every few seconds or minutes.

Slide 35



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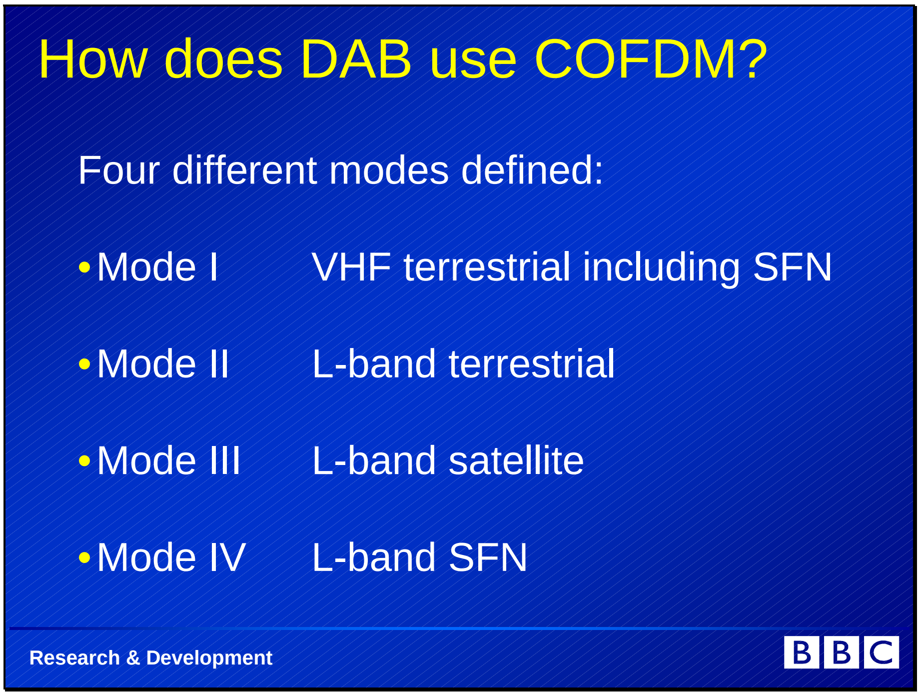

VHF – 100-300MHz

SFN – Single Frequency Network – multiple transmitters operating on a single frequency to improve reception over a wide area (e.g. the whole of the UK) which will appear as “constructive multi-path” to the receiver.

L-Band – 1500-1600MHz

Terrestrial – relatively high Doppler (e.g. driving away from the transmitter) with relatively large transmitter separation and lots of multipath.

Satellite – generally just one transmitter and high angle of incidence, hence not much multipath.

Slide 37

DAB critical parameters

Parameter	DAB mode			
	I	IV	II	III
Number of carriers	1536	768	384	192
Carrier spacing (kHz)	1	2	4	8
Symbol length (µs)	1000	500	250	125
Guard interval (µs – approx.)	246	123	61	30
Null length (µs – approx.)	1297	648	324	168
Transmitted frame length (ms)	96	48	24	24
Data symbols per frame	76	76	76	153
Time interleaving (ms)	384	384	384	384
Transmitter spacing (km – approx.)	96	48	24	12

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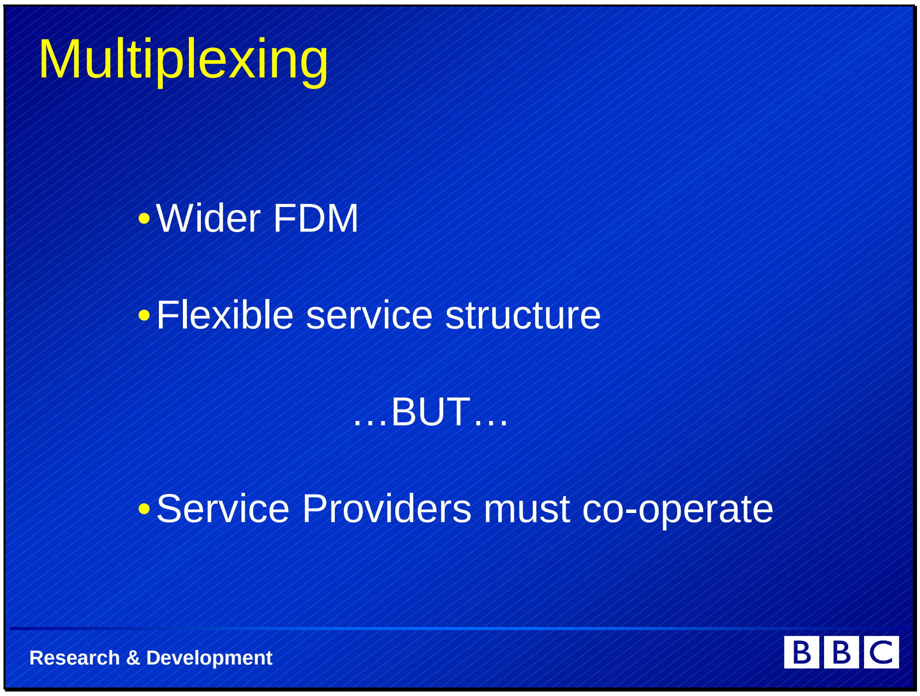
The modes are listed in a “weird” order. This is because when they were designed initially, only modes I-III were thought necessary. A logical “gap” existed in the parameters chosen (note how most parameters double or halve as you move side to side). Mode IV was added later to “plug” this “gap” when the possibility of a Single Frequency Network in L-Band was thought practical. Note that mode III is a bit of an odd-ball – the frame length doesn’t halve compared to Mode II.

Slide 38



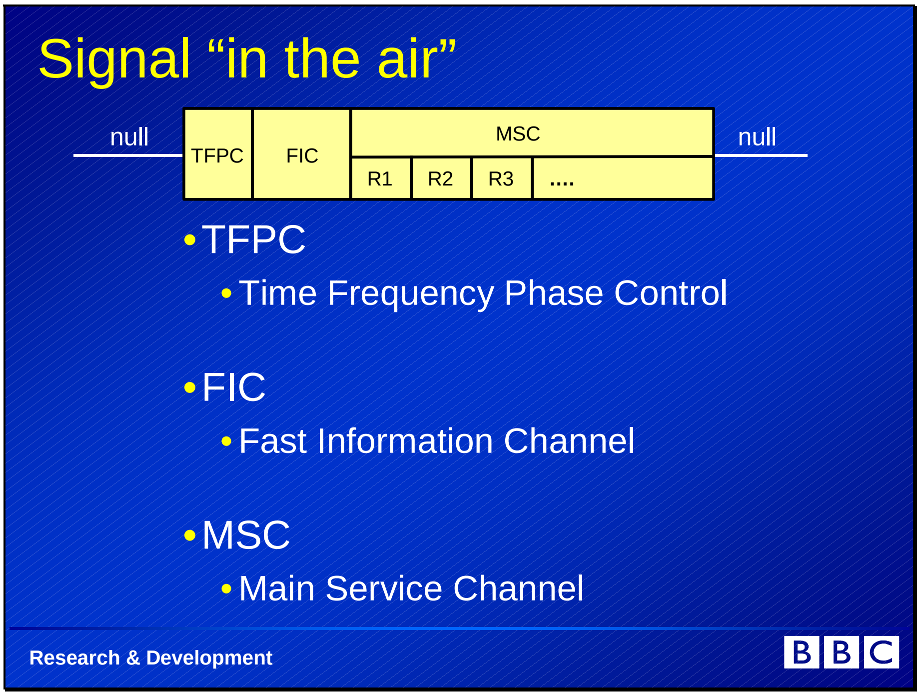
Put simply, combining several services together.

1. Instead of 150kHz for one service, 1·5MHz for ten services. Reduces the likelihood of a significant quantity of lost data. Can almost be seen as another type of interleaving – frequency domain interleaving instead of the time domain interleaving I mentioned earlier.

2. Second advantage is that the capacity can be dynamically re-allocated: e.g. “The Proms” on Radio 3 might steal some capacity from Radio 4 to improve the quality, or Radio 5 might steal capacity from Radio 3 to cover a larger number of sporting events by creating “secondary service components”.

3. Easy for the BBC, but what happens if Classic wants to “borrow” bit-rate from Capital? Commercial services less willing to exploit this functionality – indeed this is perhaps one of the biggest political stumbling blocks for DAB. Indeed, the difficulty of setting up “Multiplex Operators” that was a large part of the reason why the BBC got on air four years before the commercial broadcasters.

Slide 39



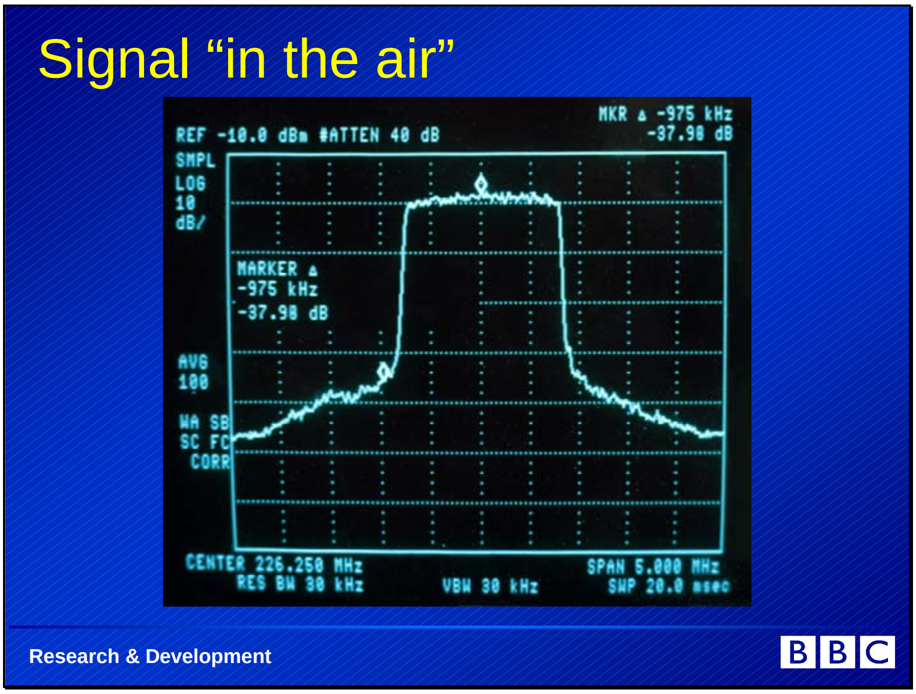
Null symbol – very coarse synchronisation, but very easy to implement.

TFPS – very fine synchronisation – a bit like the colour-burst in analogue TV.

FIC – all the information about what is carried in the MSC

MSC – the actual audio or date we want to broadcast.

Slide 40



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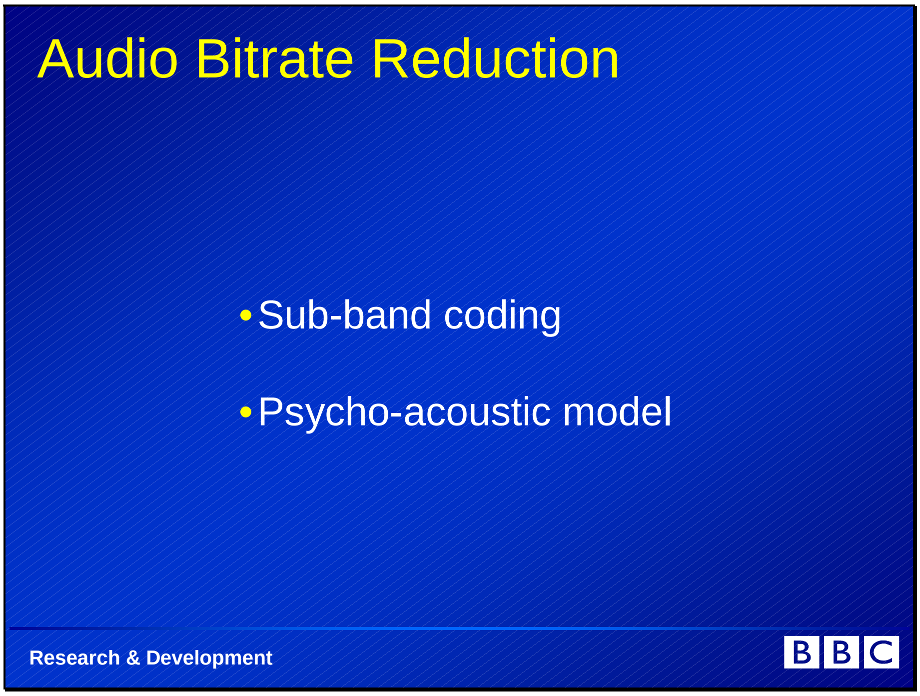

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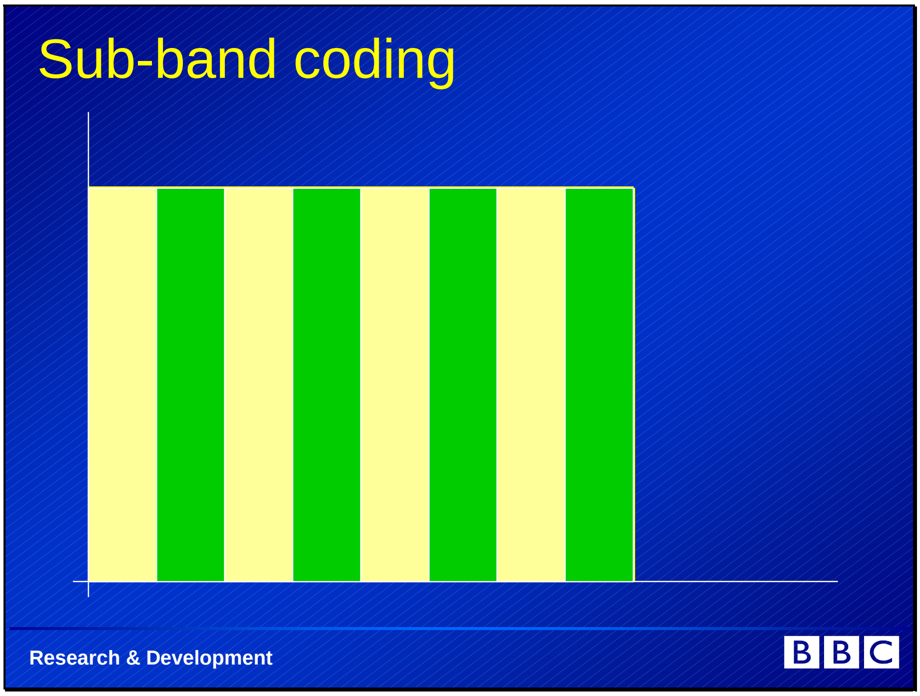
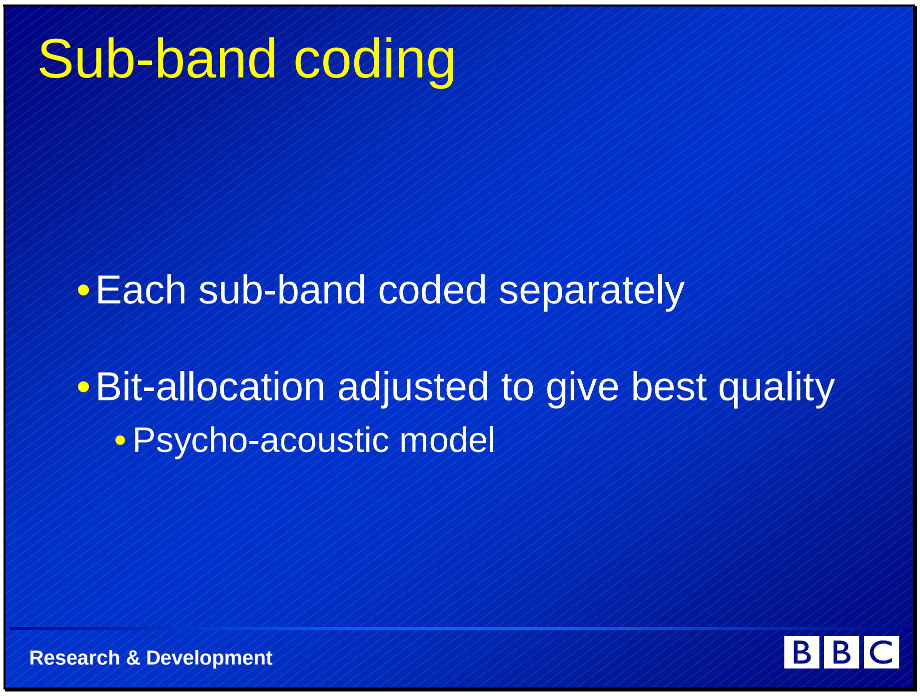


First the audio is split into a number of sub-bands, each covering a narrow part of the audio spectrum. Each is analysed and encoded separately. The results of the analysis are used to determine how many of the available bits are actually necessary in order that the decoded signal will be indistinguishable from the original – and deciding that is where the psycho-acoustic model comes in.

Slide 43



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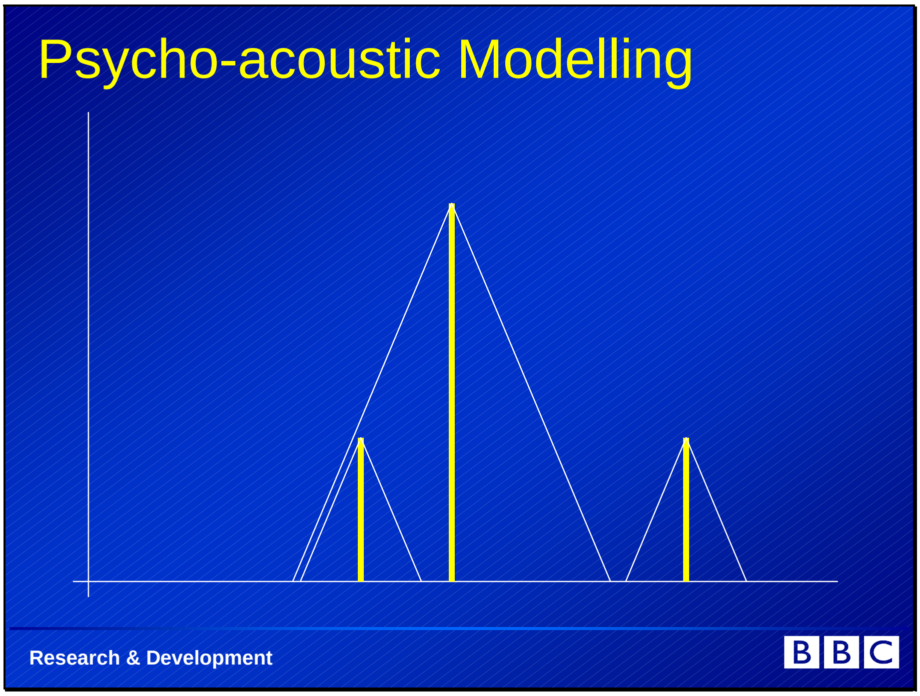
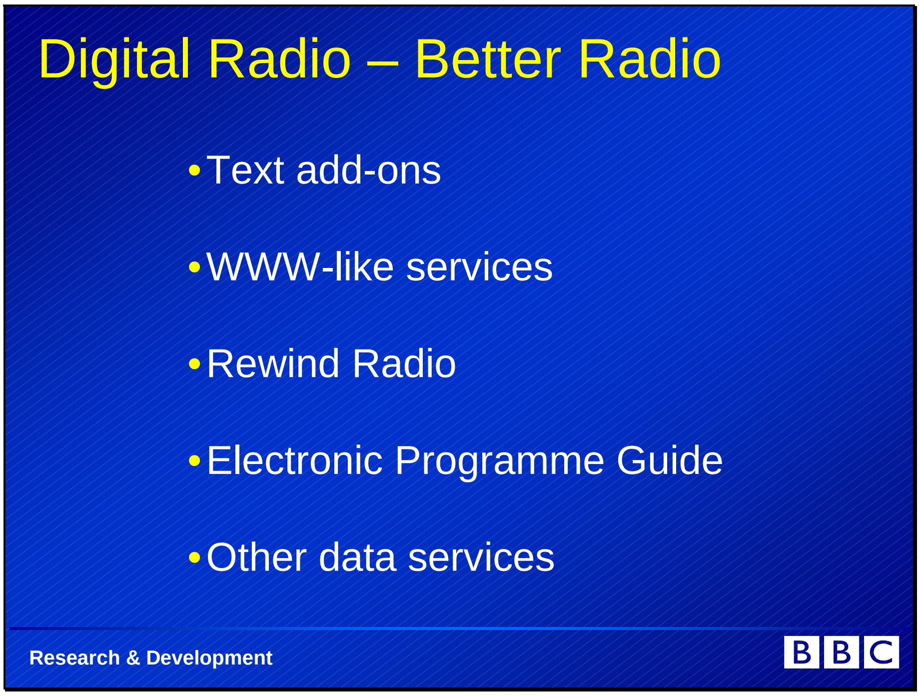


Imagine we had a very simple audio signal comprising three tones. The way the human ear works means that a loud tone will "mask" any nearby quieter tones. The psycho-acoustic model tries to map this masking, but of course everyone's ears are slightly different. The trick is to find a model which works well for the widest possible range of people, young and old, male and female – even the nationality of the person makes a difference, especially to speech, as the range of sounds the brain is used to hearing varies. This can only be determined by running experiments where willing volunteers subject themselves to the same piece of music over and over again, grading each as "excellent", "good", "poor" etc. Once enough experiments have been conducted, the model can be adjusted and the tests re-run.

Slide 45

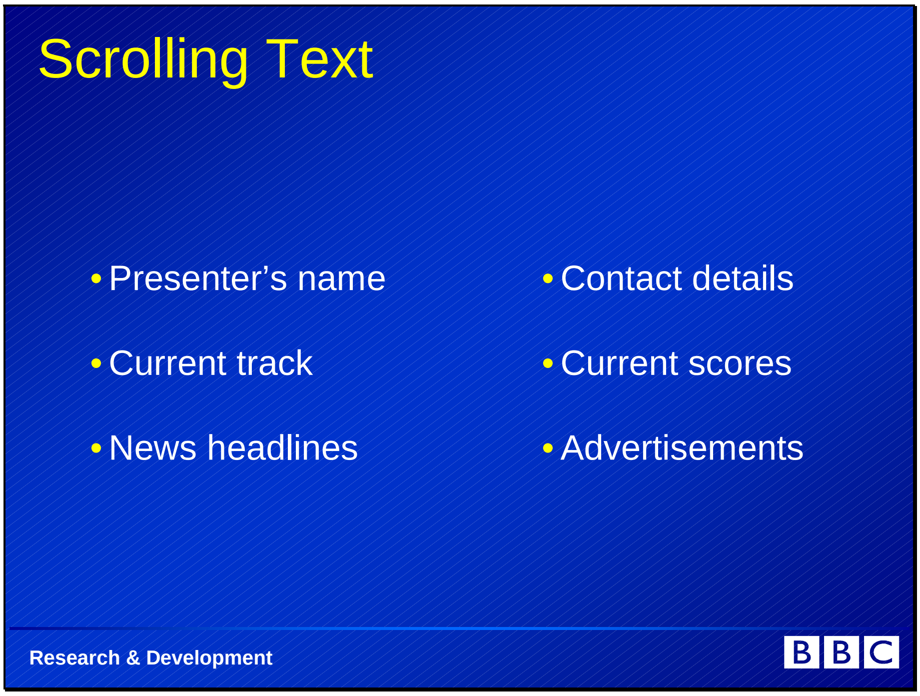
OK – so we've covered the technology behind DAB, which is interesting to the engineers amongst us, but how does all this technology help the people who matter, the users?

Slide 46



No one thing is going to appeal to every radio user, but DAB allows us to broadcast many different things. The trick is deciding what to broadcast to ensure that everyone gets something they like. As you can imagine, people's needs and desires vary hugely, and so the range of things the DAB has to do also has to vary. Some examples include:

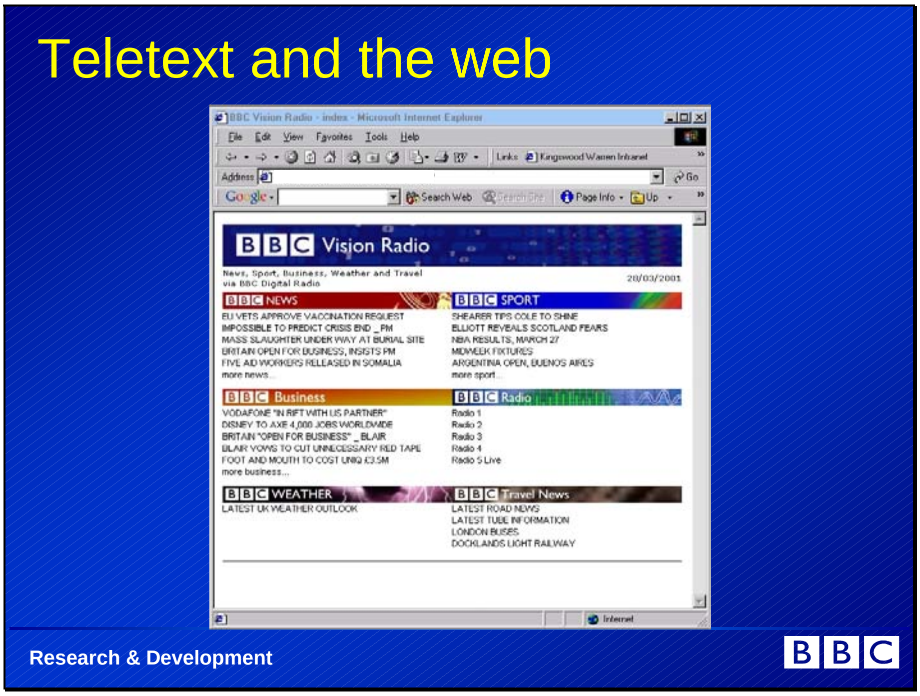
Slide 47



Short text directly associated with an audio service. Most receivers display this on a single-line scrolling display, but some offer larger panels allowing the whole text to be seen at a glance.

Ideal for “value added” text – track information, what’s on next programme trailers, latest football scores etc.

Slide 48

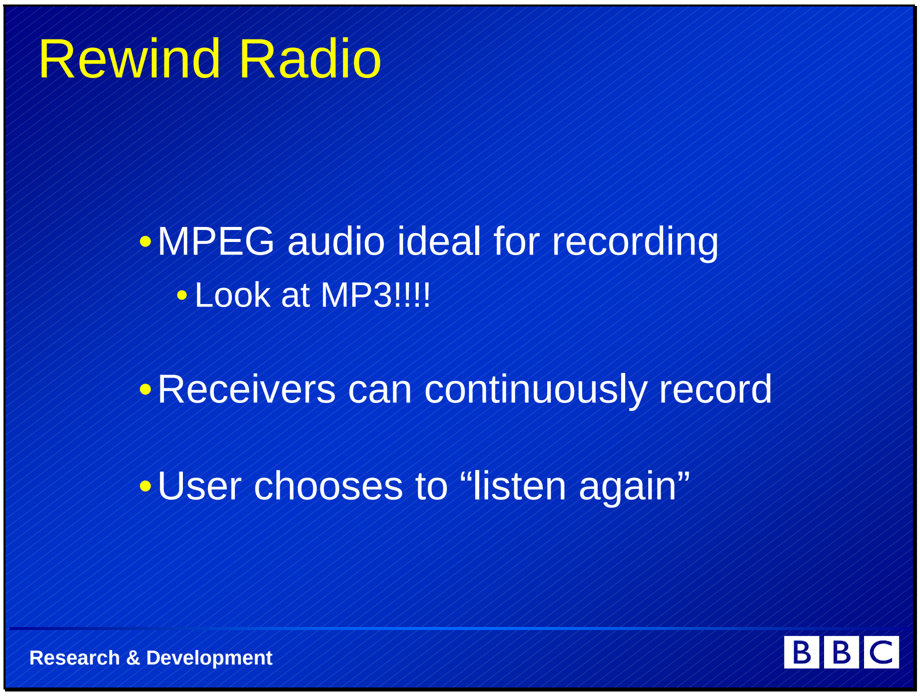


BBC Vision Radio and the Digizone on air as pilot services

Vision Radio re-versions Ceefax as web-pages

Receiver caches the pages locally and displays them “instantly” on a PC connected to the receiver, or on a display built in to the receiver. The early experiments used HTTP/HTML as the “standard interface” to allow any web browser to access the content.

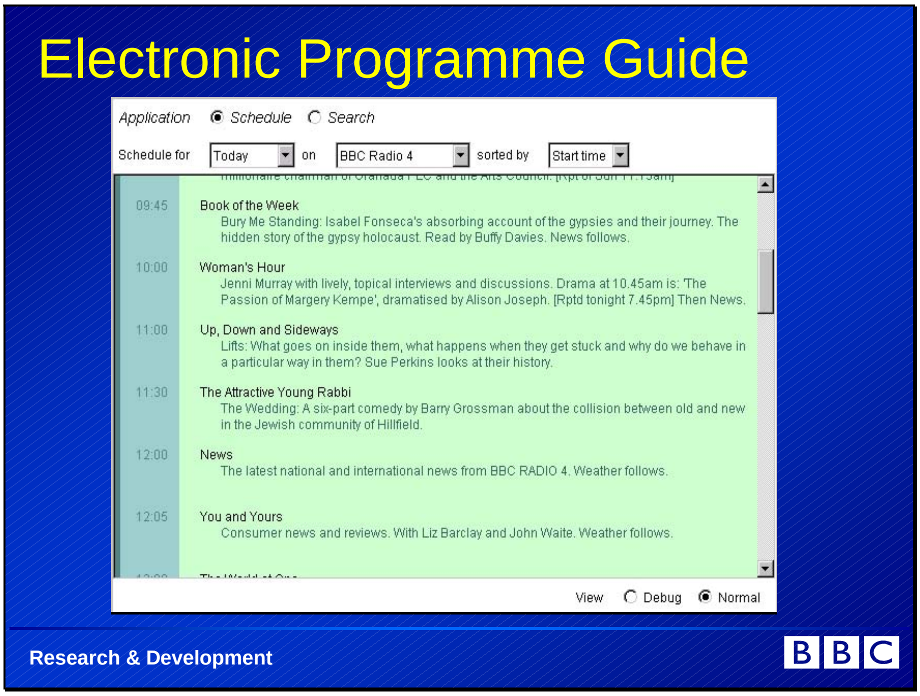
Slide 49



Memory card or integrated memory

Go back and listen to the phone number again

Slide 50



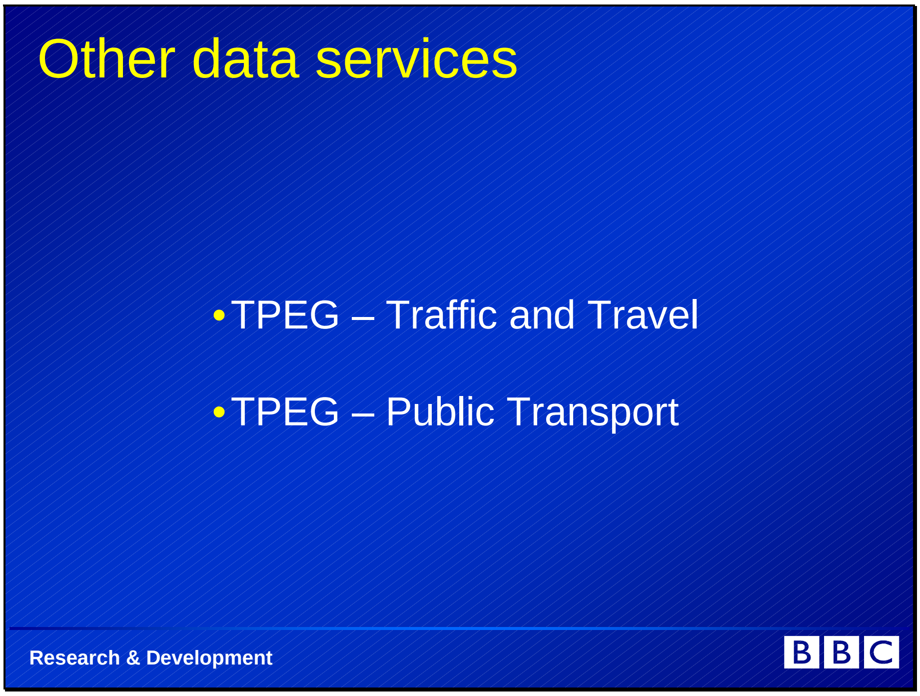
What's on when?

Searchable database

Scalable from personal receivers through to PC receivers

Timed recording

Slide 51

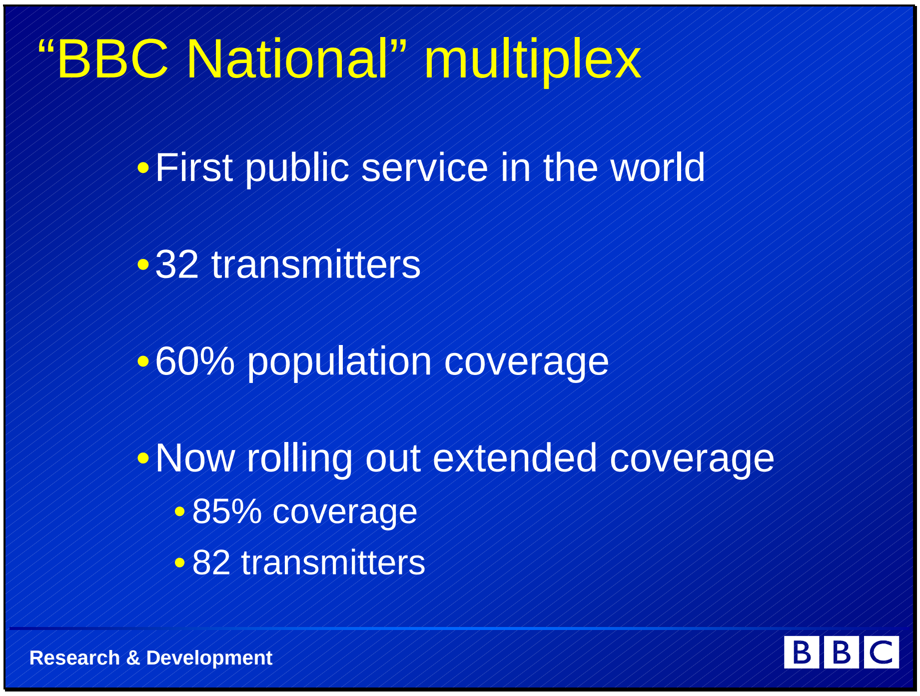


TTI - BBC pilot service on air since 1999 - Receiver development ongoing, but no in-car receiver links to Satellite Navigation systems yet.

PTI – standards being drawn up and published, some interest from some public transport providers, needs decoder to be integrated into "personal receiver" to be of real benefit, but not yet achieved.

Slide 52

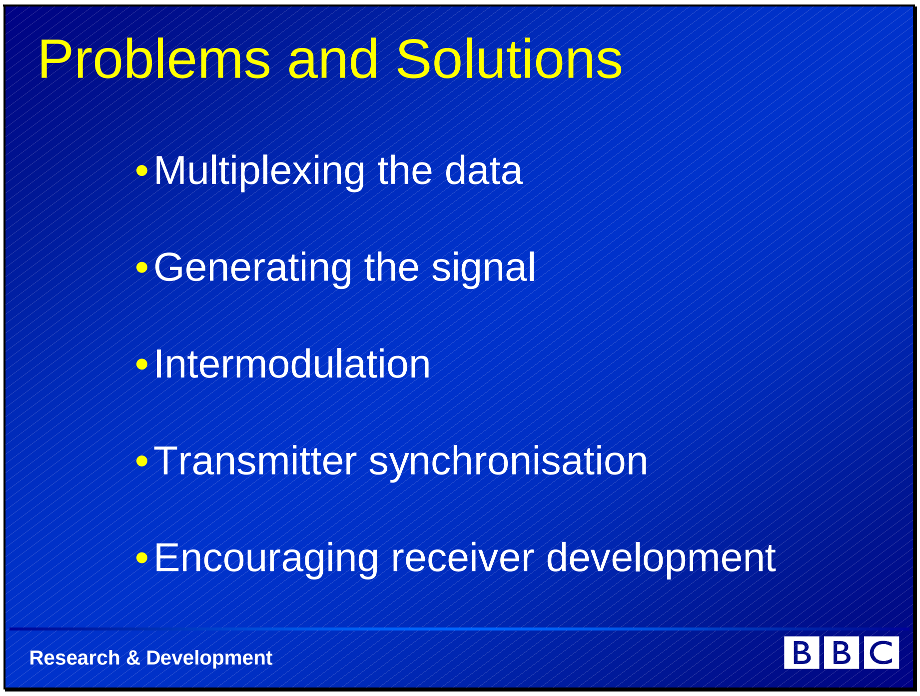
Slide 53



27th September 1995

Sweden on the same day, but they withdrew for a few years due to the lack of receiver support. I'm pleased to say that Sweden are now back on air, and many other countries in Europe and around most of the rest of the world have at least pilot DAB services on air, and most receivers available now can be used to receive these transmissions – what started as a European project has become a world-wide standard.

Slide 54



Slide 55

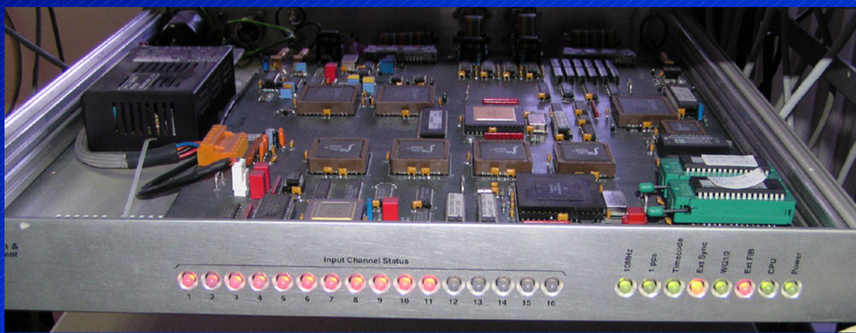
How much equipment…?!!

Research & Development

BBC

Slide 56

Multiplexing the Data



Research & Development

BBC

Slide 57

Generating the signal

- DAB uses up to 1536 carriers
- 2048-point Fast Fourier Transform
  - Generate data in frequency domain
  - Convert to the time domain (I-FFT)
  - Transmit the signal
  - Receive in the time domain
  - Convert back to the frequency domain (FFT)

Research & Development

BBC

Slide 58

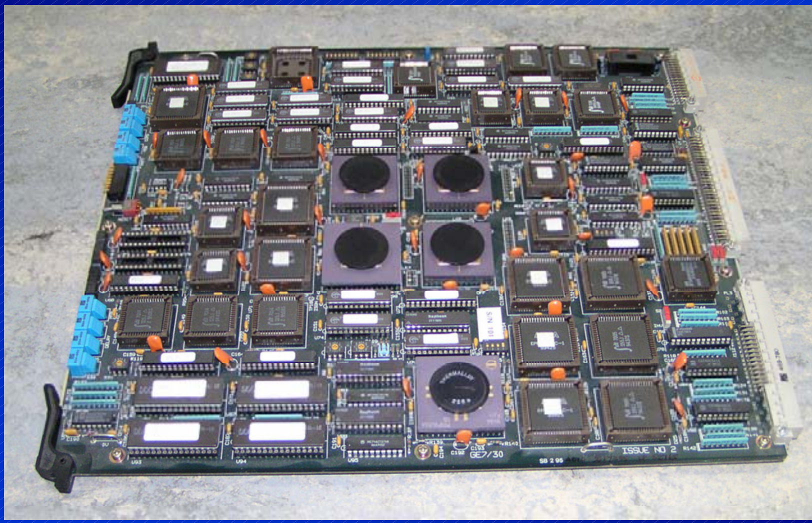
BBC COFDM Coder – circa 1992

Research & Development

BBC

Slide 59

1992 FFT Engine



Research & Development

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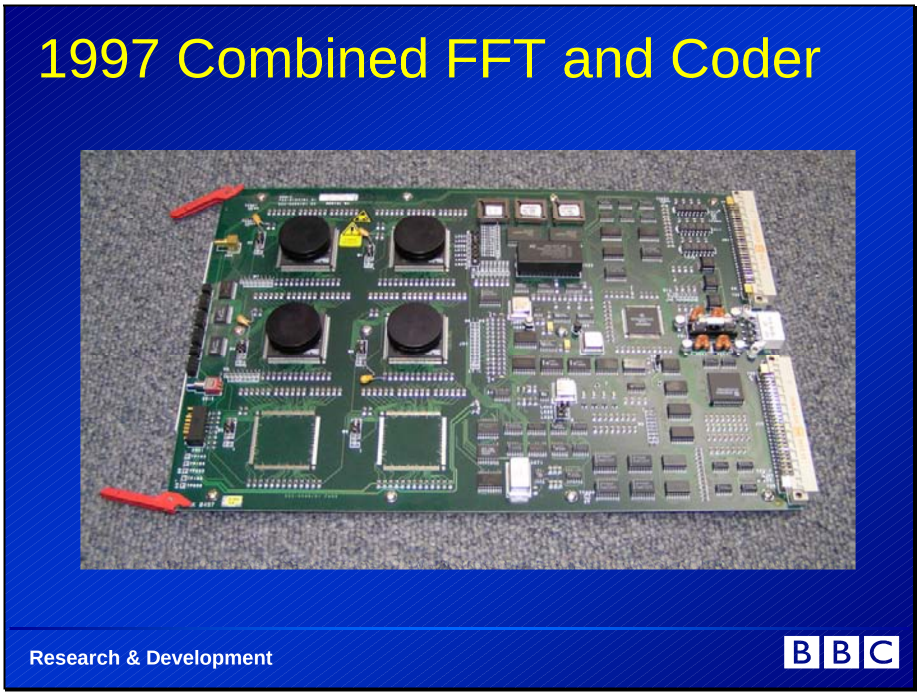
Slide 60

1992 Convolutional Coder

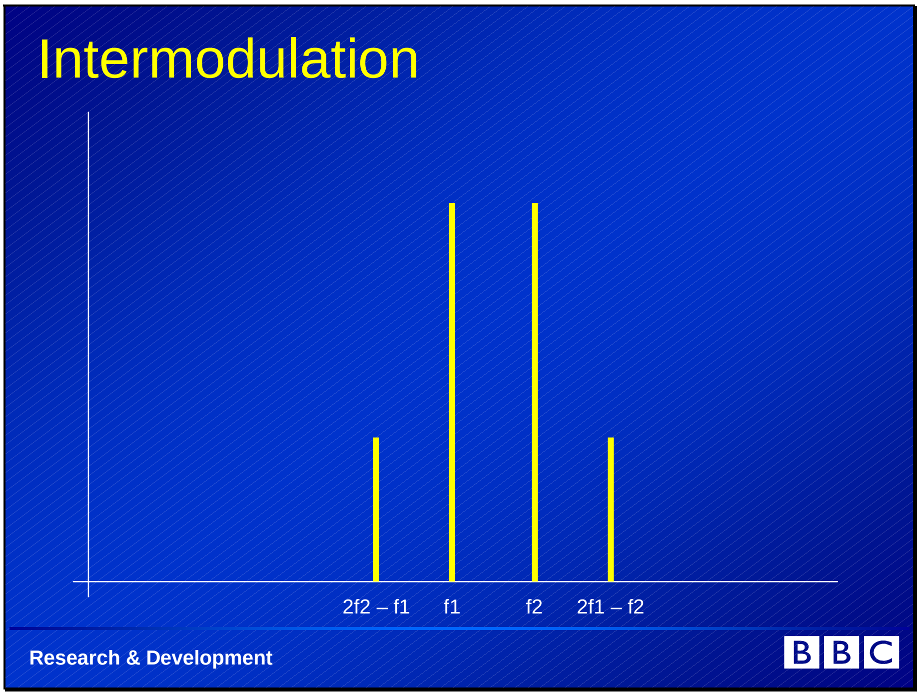
Research & Development

BBC

Slide 61



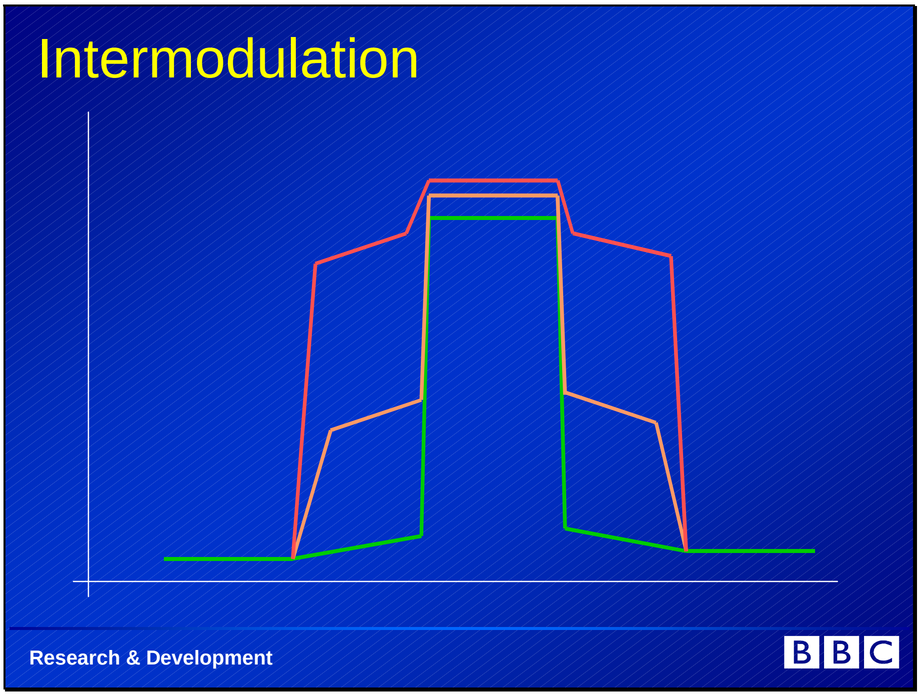
Slide 62



Most electronic circuits are inherently non-linear, but can be linearised. For complex waveforms like the transmitted DAB signal, any non-linearity can cause problems. Consider the simple case of an amplifier for a signal comprising two simple tones of frequencies f1 and f2. A perfect amplifier would produce an identical output signal, albeit with greater power. Non-linearities in the amplifier result in spurious tones being generated at any (and possible all) frequencies $\pm n \times f1 \pm m \times f2$ where n and m are integers - we call this "Intermodulation". Of particular concern are the 2f2-f1 and 2f1-f2 frequencies since these are generally quite close to the wanted frequency and can't be filtered out using conventional filters.

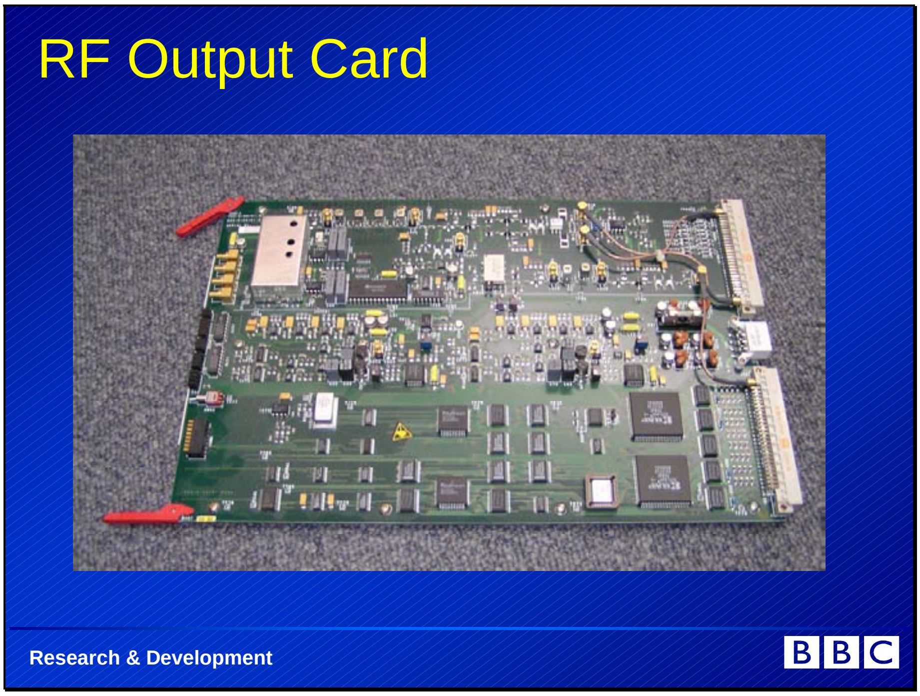
Now consider DAB. No longer do we have 2 tones - we have up to 1536. Many of the spurious tones actually coincide with other wanted tones, and are thus completely impossible to filter out.

Slide 63



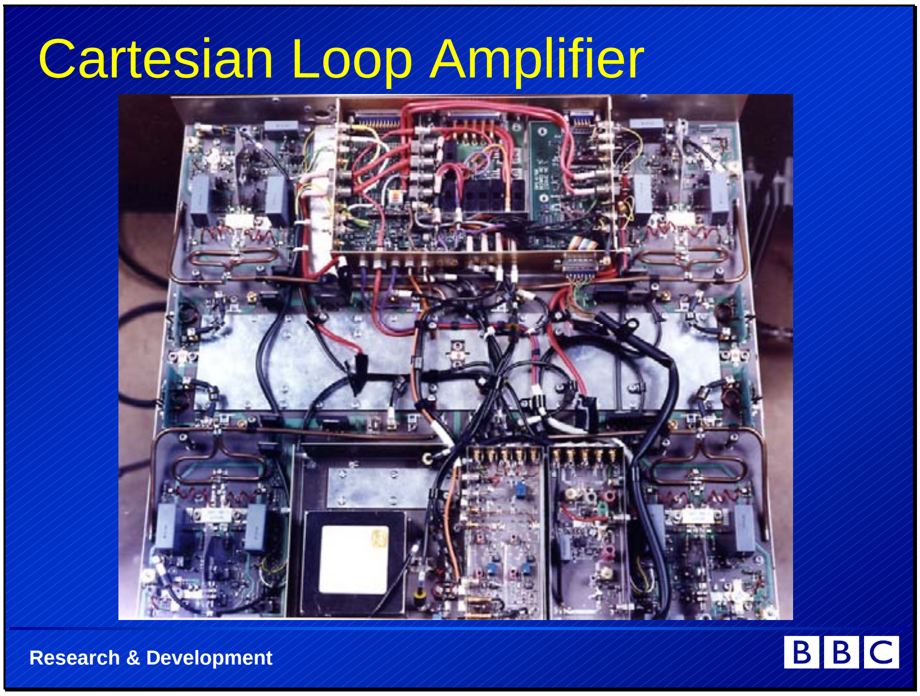
As the wanted output power goes up, so do the sidebands generated by intermodulation. Just a couple of dB more output power can have a massive effect on the sidebands, and don't forget, those sidebands are exactly on top of the next DAB service.

Slide 64



The RF card therefore had to be designed to be very linear, so that the output spectrum was as pure as possible. However, this card could only produce a few milliwatts of power – and we needed transmitters of around 1kW…

Slide 65



Cartesian Loop Amplifier

Power amplifier

- Separate linearisers for I and Q signals
- 35W per amplifier

4 amplifiers per tray

8 trays per bay

1kW LINEAR per bay

- 4kW from the mains

…so we had to build a linear power amplifier, and if we thought the RF output card was hard, the power amplifier was worse. In the end we had to design not just a linear power amplifier, but a feedback lineariser as well.

If we used it for FM, we could output about 3kW.

But, this 1kW transmitter carries TEN services, and actually covers a larger geographic area than a 5kW FM transmitter, so in fact DAB is a lot more power efficient to transmit than FM.

Slide 66

Transmitter synchronisation

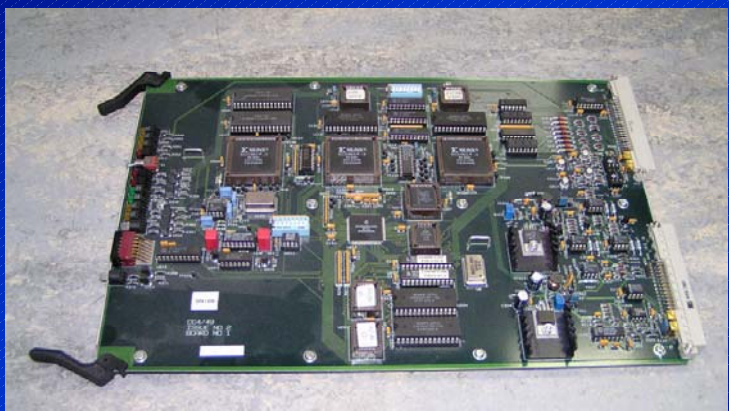
- Accuracy of timing
  - ±100ns across the country
- Use GPS

Research & Development

BBC

Slide 67

Network Adaptor – Sender

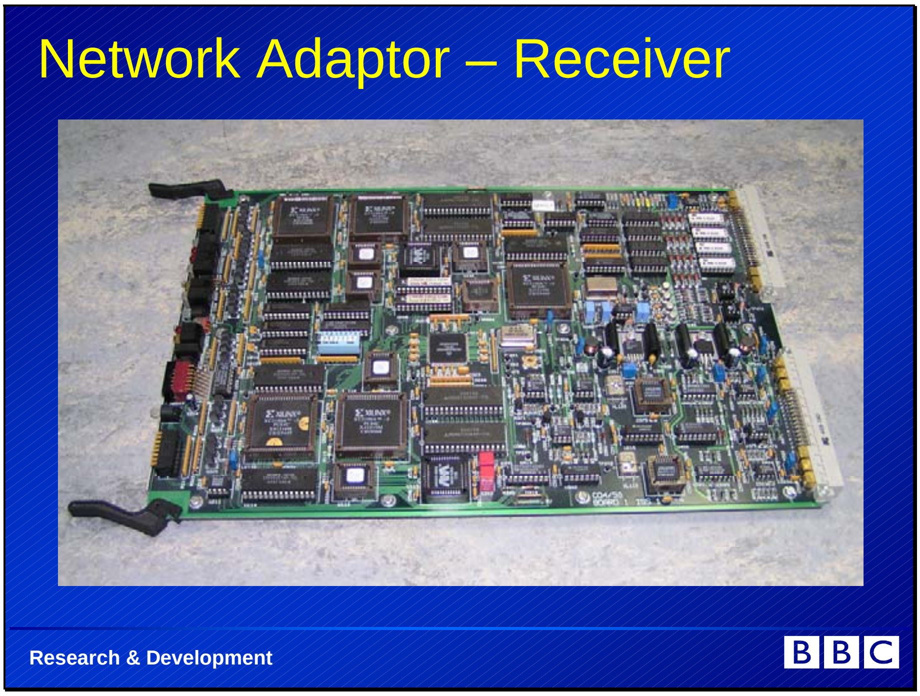


Research & Development

BBC

This device sits in Broadcasting House and embeds a timestamp into the signal sent to the transmitters.

Slide 68



This devices sits in the transmitter itself and compares the incoming timestamps with the GPS reference, buffering the data until the right time for the signal to be transmitted.

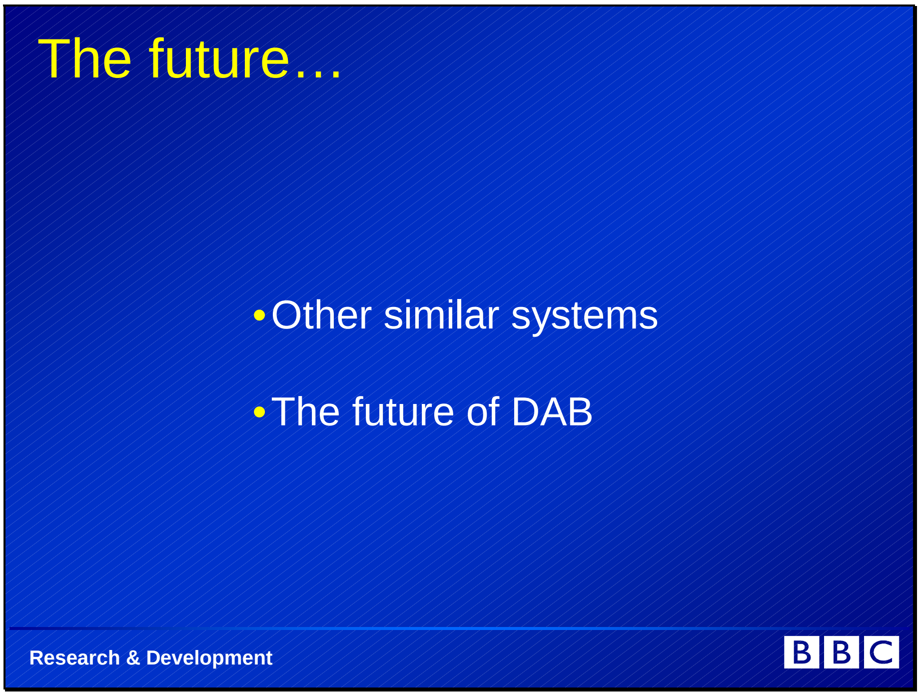
Slide 69

DAB test equipment VERY expensive

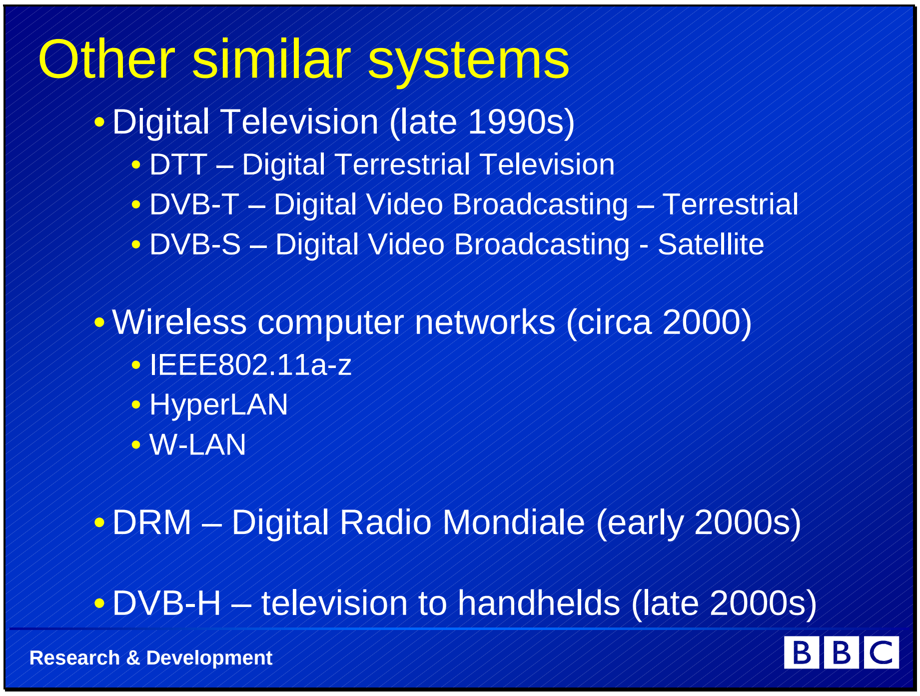
BBC ran a Test Lab for many years

Affectionately known as the “torture chamber”!

Slide 70

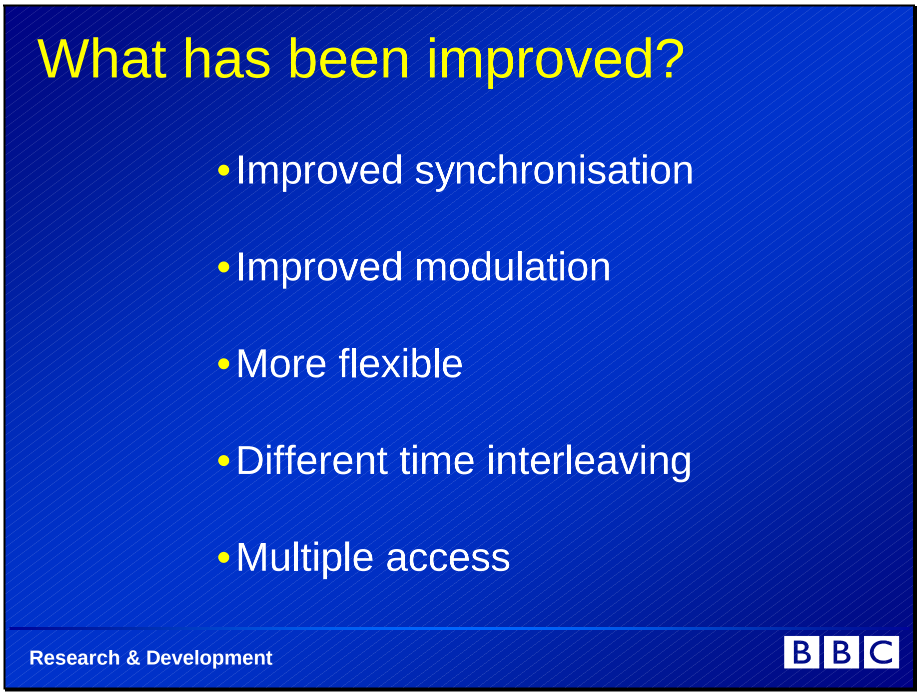


Slide 71



DRM – digitising the shortwave bands (<30MHz). DAB directly addresses the VHF through to the low microwave bands (30MHz – 3GHz) but the choice of parameters for shortwave, medium-wave and long-wave bands are significantly different due to the radically different propagation parameters found in these bands.

Slide 72



1a. DTT and DRM don't have the null symbol for synchronisation, allowing more "time" for real data and thus increasing the capacity of the system.

1b. The TFPC reference symbol has been spread (in time) across "pilot carriers". Since the receiver can use the pilot carriers to "estimate" the channel characteristics, it can compensate for some of the distortion give extra information to the Viterbi decoder to improve the error performance

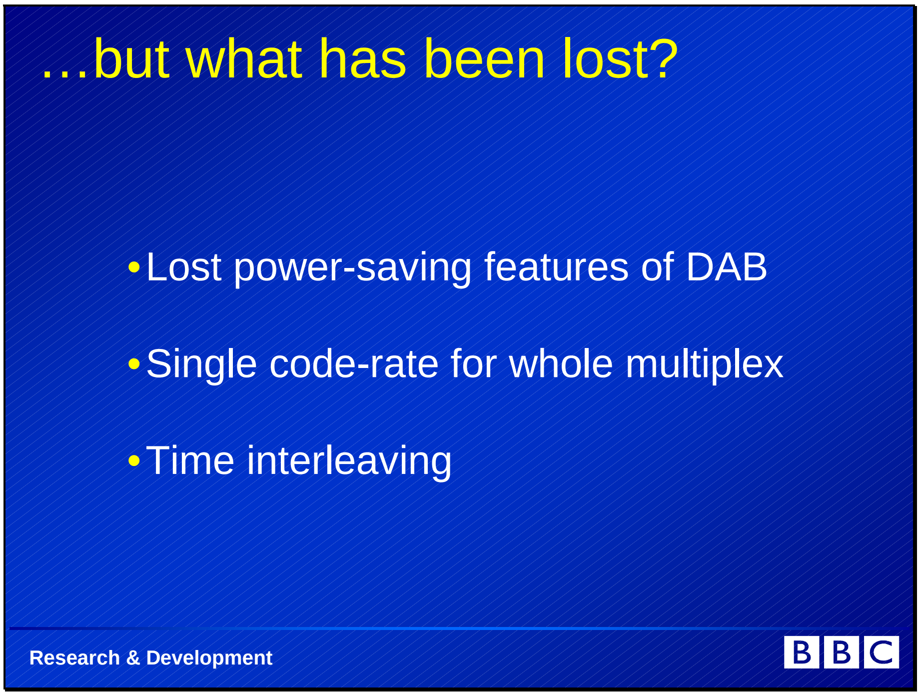
2. Use of pilot tones also allows coherent demodulation (instead of differential demodulation) giving a further (slight) increase in capacity. π /4 DQPSK replaced by 4-QAM (aka QPSK), 16-QAM and 64-QAM, and in future even by more advanced schemes

3. DAB has four modes – DTT/DVB-T has 24 modes (2K/8K, 4/16/64-QAM,4/8/16/32-GI), DRM has 60+ modes. Allows more options for the broadcaster to choose the best compromise for reliability versus capacity.

4. DTT doesn't have time interleaving at all! Makes decoding much quicker (channel surfers love it) but means that burst errors (e.g. caused by the central heating switching on and off) may exceed the correcting capability of the Viterbi error correction, resulting in blocking and/or picture break-up.

5. Computer networks are (normally) bi-directional, unlike broadcast networks. IEEE802.11 has had to build in application layer protocols to handle "collisions" between different transmitters, something which the BBC didn't have to worry about when rolling out DAB or DTT.

Slide 73

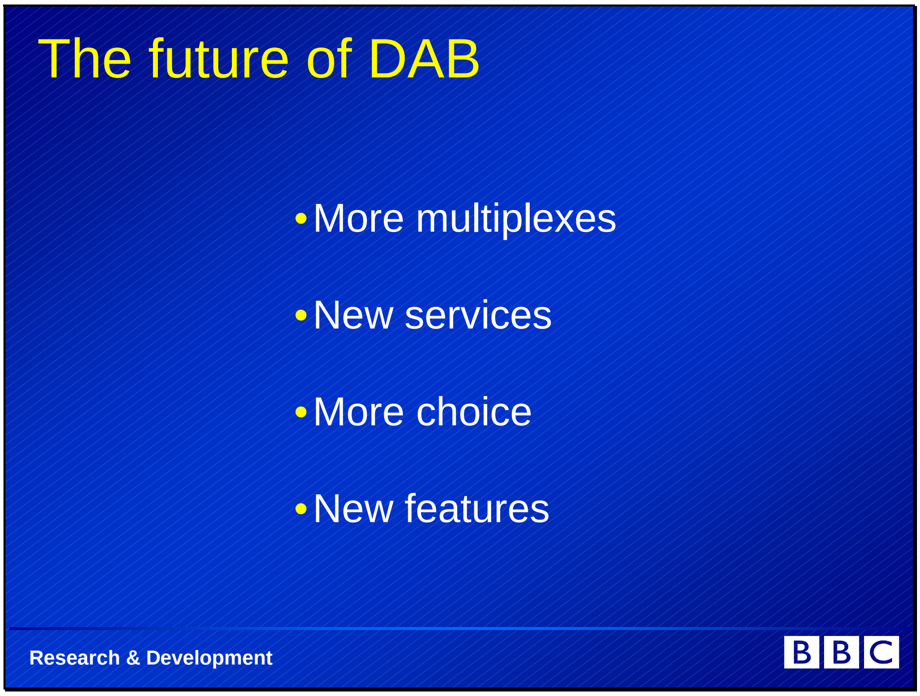


1. DAB was designed for handheld and in-car reception, and was therefore designed with many power-saving features in mind. For example, the RF circuitry can typically “go to sleep” for about 80ms out of every 90ms once the signal has been initially acquired – a DVB-T receiver can’t do this.

2. DAB offers unequal error protection, such that data which is absolutely critical is much more strongly protected by the convolutional code. For example, losing the header for an audio frame causes the entire frame to be lost, while losing a single sample is hardly noticeable. Most later systems don’t offer this flexibility – all of the data is treated equally.

3. Perhaps surprisingly, some systems don’t use time interleaving. Yes, it does have some effect on the rate of channel hopping, but it has a much bigger effect on the robustness of the system.

Slide 74



Slide 75