EEENGM4221:

Broadband Wireless Communications

Solutions

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Some Solutions (1)

- As we have seen, facilitating Broadband Wireless Communications imposes some significant challenges:
  - Spectral Efficiency
  - Significant Channel Impairments
    - Slow/Fast Fading
    - Interference
  - Medium and Multiple Access requirements
  - QoS demands

Some Solutions (2)

- Not surprisingly, we require many tools in our Engineering ‘toolbox’ to tackle these challenges
- Many of these tools are covered elsewhere:
  - – Fading can be mitigated by Diversity (EENG32500)
    - Time, Frequency, Space/Polarisation
  - – Dispersion can be mitigated by:
    - Equalisation (EENGM2510)
    - Multicarrier (EENGM2510)
    - Spread Spectrum/CDMA (EENGM2510)

Ref:

Some Solutions (3)

  - Errors in General can be mitigated by Error Control Coding (EENGM2011)
- We will not duplicate these here. However, we will introduce some others:
  - Link Adaptation (mitigates free space and shadowing loss)
  - Dynamic Resource Allocation (Multi-user Diversity)
  - HARQ

Ref:

Link Adaptation (1)

- Link Adaptation involves changing the parameters of a communications system to accommodate variations in Link Quality
- As we have discussed the 'quality' of the Link can vary substantially
- With a fixed (non-adaptive) system, we must either:
- Design for the worst (or at least a bad) case and accept that the system under performs some of the time
- Design for the best (or at least a good) case and accept that the system fails some of the time

Ref:

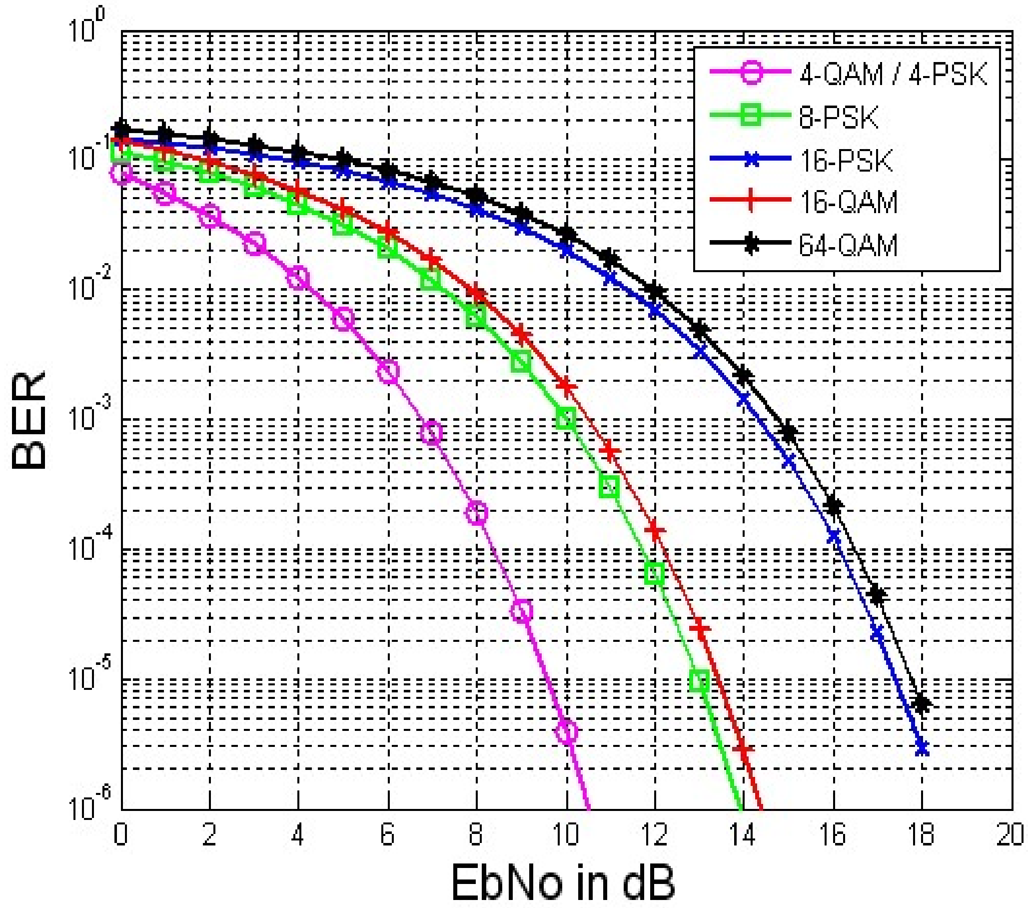
Link Adaptation (2)

- Alternatively, if we adapt to the link, we may be able to achieve a better result, a system which:
  - Works very well given a good link
  - Works adequately given a bad link
  - Works moderately well in a moderate link,
  - Etc
- i.e. a system which gets the best available result given the current conditions
- What do we mean by ‘works well?’
  - Usually how much throughput is achieved whilst maintaining QoS.

Ref:

Link Adaptation – Simple Example (1)

- Consider a communications system employing QAM:
- BER performance is well known:

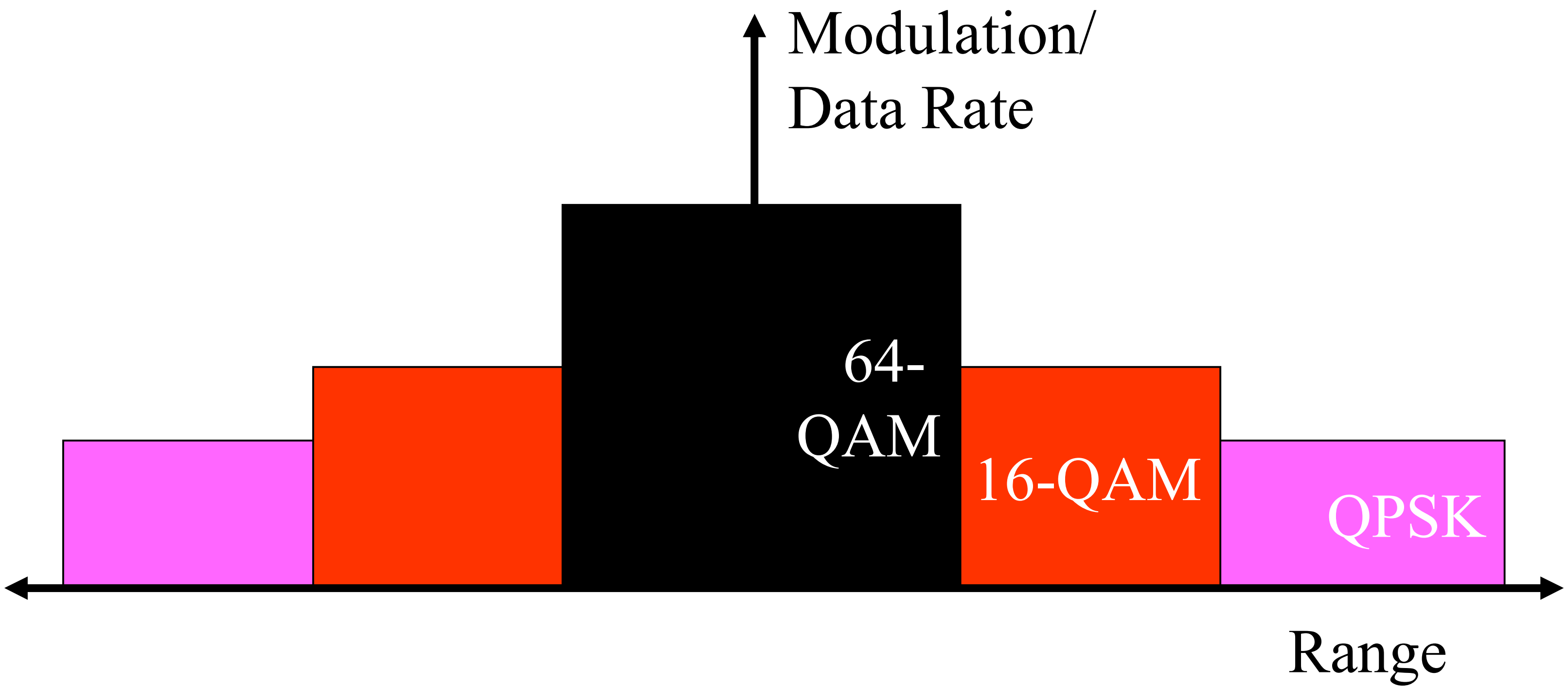


Ref:

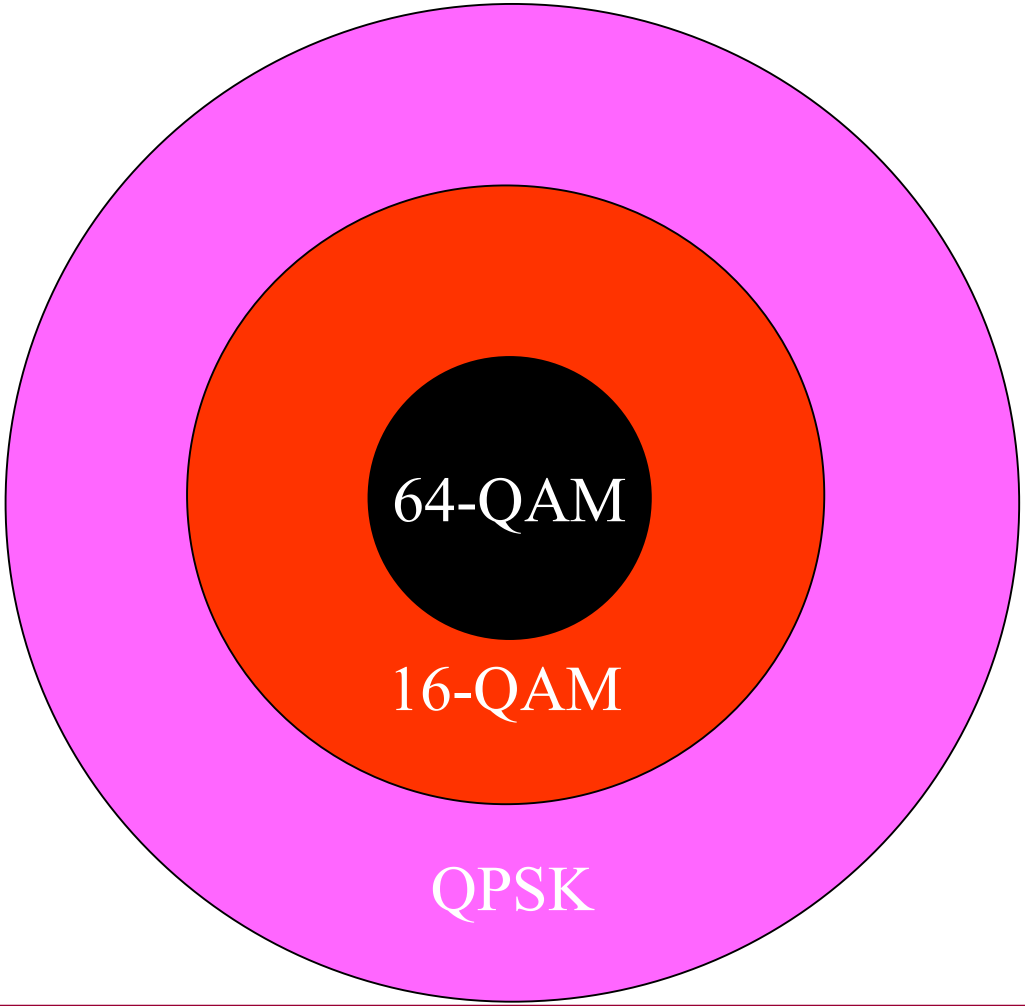
Link Adaptation – Simple Example (1)

- Assuming we need a BER 10^{-6}, we could use:
  - QPSK in which case we get 2bits/s/Hz and need ~13dB SNR
  - 16-QAM in which case we get 4bits/s/Hz and need ~18dB SNR
  - 64-QAM in which case we get 6bits/s/Hz and need ~27dB SNR

Link Adaptation – Simple Example (2)



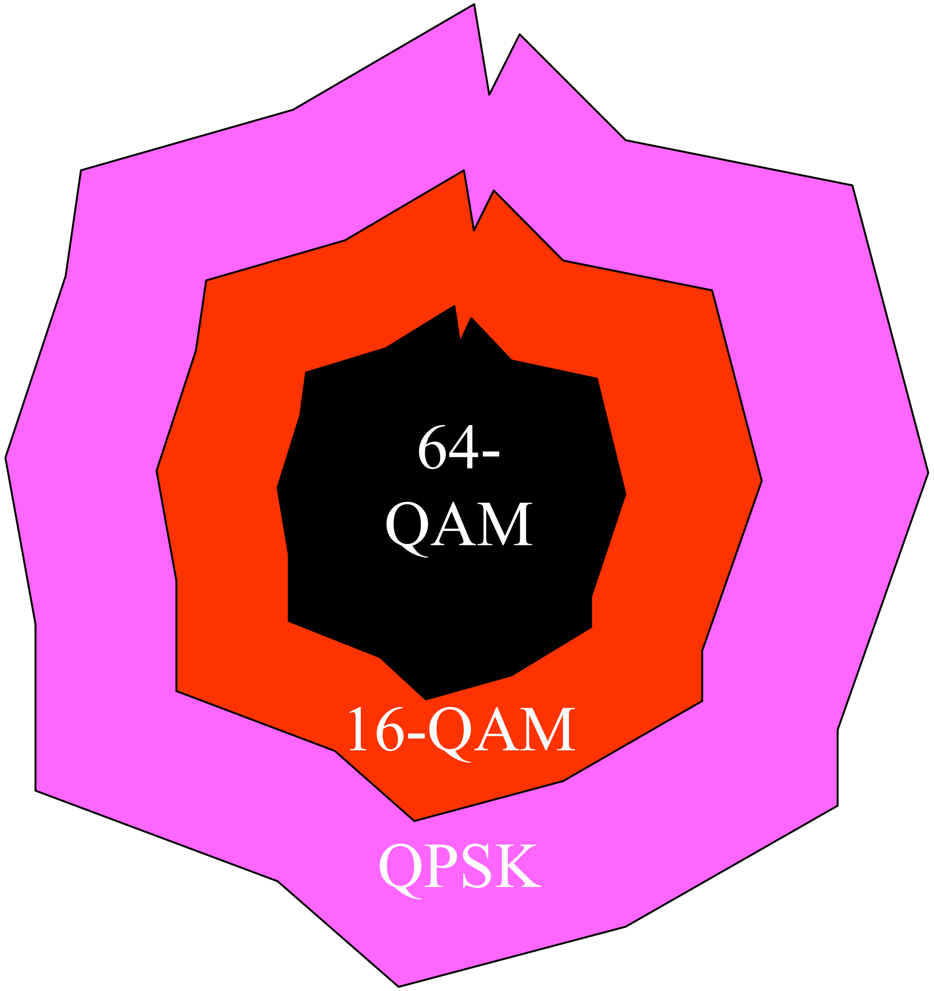
Link Adaptation – Simple Example (3)



- Circles aren't very realistic really…

Ref:

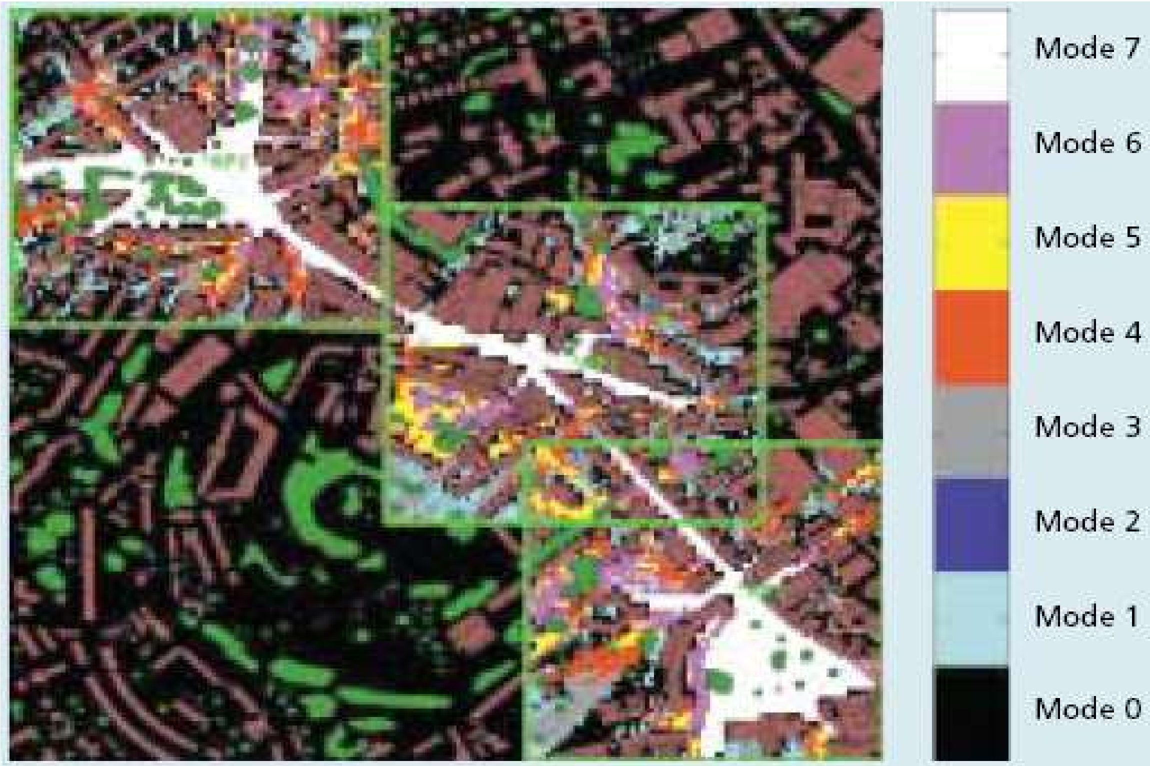
Link Adaptation – Simple Example (4)



- More Realistically, allowing for Shadowing Effects, the coverage areas won't be circular
- A bit like a contour map but showing data rate, not altitude

Ref:

Link Adaptation – Real Example



- Mode Selection on the Triangle.
- Considers 802.11a (8 modes BPSK-64-QAM and ½ - ¾ rate codes)
- Finer Granularity
- Source: CCR

Ref:

Link Adaptation – Per User QoS

- Link Adaptation is very useful when trying to provide QoS
  - Provides a mechanism for trading off data rate vs reliability (PER and hence delay and loss)
- LA can also be applied on a per user basis e.g. to give one user with a weak signal lower throughput whilst also giving another with a better signal a higher throughput
  - The overall throughput will be the aggregate of all the users
- LA is not a panacea:
  - Poor signal still gives poor data rate
  - It is not a guarantee of QoS

Link Adaptation – Its Out There

- Link Adaptivity is now recognised as a vital feature for modern Communications systems
- GSM added LA for GPRS (code rates)
- UMTS had limited LA capability from the outset (code lengths)
  - More support added later in HSDPA and HSUPA (modulation and coding)
- 802.11 started with limited support for LA (packet size)
  - Later added explicit support for LA for a,b,g,n (modulation and coding rate)
- Bluetooth has limited LA capabilities (code rate and packet size)
- 802.16 incorporated LA from the outset

Dynamic Resource Allocation (1)

- Dynamic Resource Allocation is a Strategy for exploiting Multi-user Diversity
- The merits of other sources of diversity (Space, Time, Frequency, Polarisation etc) have been considered elsewhere
- Multiuser Diversity is another opportunity which is beginning to garner interest in Wireless Communications

Dynamic Resource Allocation (2)

- We have seen that signal quality may vary substantially in several domains
  - Space (shadowing, non-isotropic radiation)
  - Time (free space, shadowing, narrowband fast fading)
    - Assuming there is some mobility in the channel, temporal change=spatial change
  - Frequency (wideband fast fading/frequency selectivity)

Dynamic Resource Allocation (3)

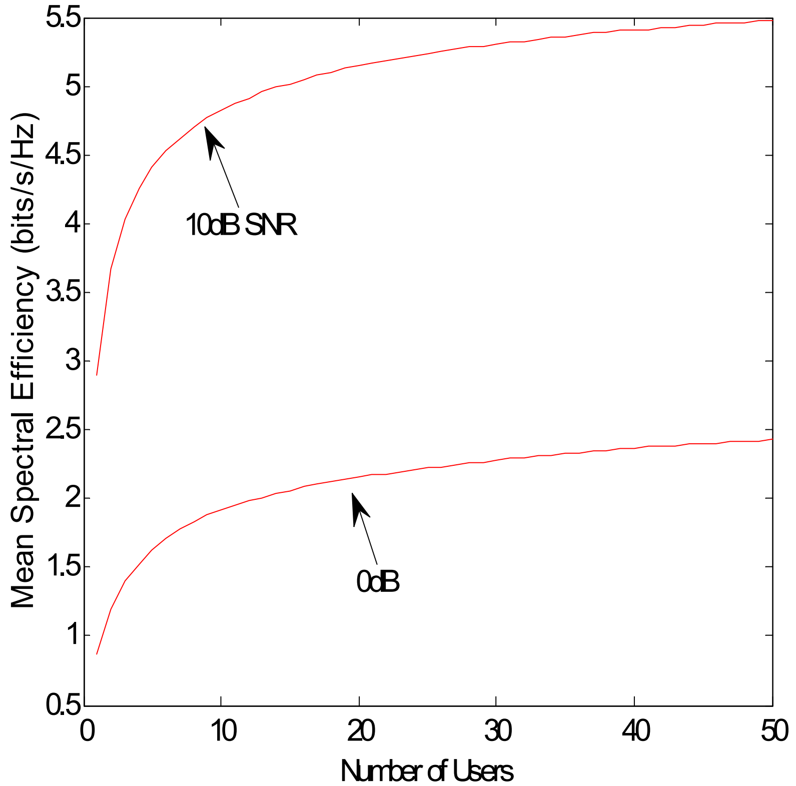
- The total available channel resource for the system will be divided between the links in the system by means of a Multiple Access strategy
- The variation in signal quality will affect the capacity of the individual links
- The capacity of the communications system as a whole will be the weighted sum of the individual links

Dynamic Resource Allocation (4)

- The idea of Dynamic Resource Allocation is to allocate channel resources to different links dynamically with the aim of enhancing QoS
  - Allocate any given resource to the link which can make the best use of it
  - DRA can only exploit diversity in a domain in which it able to perform allocation – i.e. the domain(s) of multiple access

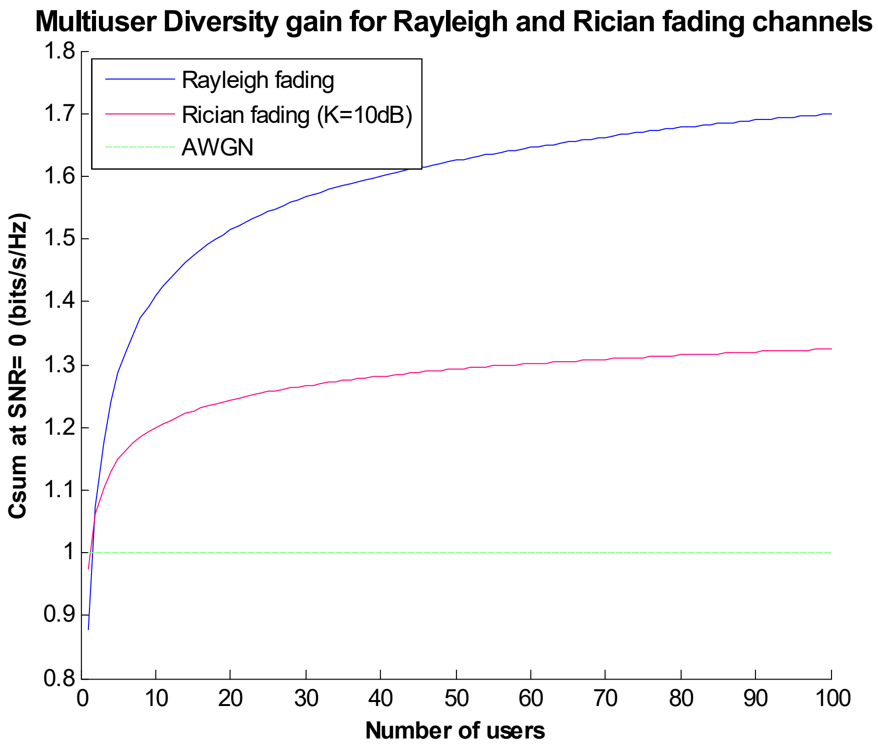
Theoretical Greedy Efficiency

- This figure shows the theoretical spectral efficiency achievable in multiuser systems under Rayleigh fading
- Capacity increases with the number of users as there is more diversity
- As with all diversity the benefits reduce as the diversity order increases
- Capacity is higher at higher SNR but increases less rapidly with the number of users



Greedy Multiuser Efficiency in Rayleigh, Rician and AWGN

- The benefits of multiuser diversity also depend upon the amount of fading.
- For AWGN, there is no fading and hence no capacity gain, no matter how many users there are
- Since the fading in a Rician channel has less variance than a Rayleigh channel, the capacity gain with increasing numbers of users is less



Ref:

Dynamic Resource Allocation – Capacity vs Fairness

- DRA can essentially be used in two ways:
  - To improve capacity – put more resources where the signal quality is good
    - Overall capacity is improved, but
    - Links with good signals get even better/links with bad signals get even worse
  - To improve fairness – put more resources where the signal is bad
    - Can balance out the effects of signal quality, but
    - Overall capacity is reduced
- Compromises are possible

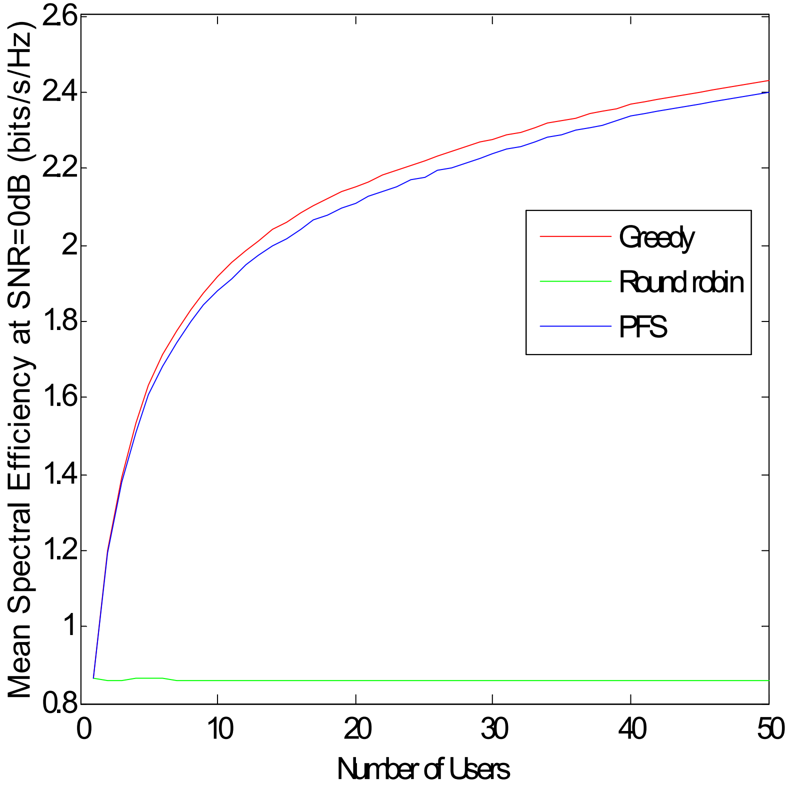
Dynamic Resource Allocation – Time Averaging for Fairness

- Some degree of fairness can be provided if the signal quality is time variant
- Over time, each users signal should vary across the range of signal quality
- Over a sufficient period of time:
  - signal quality should average out between users, hence
  - Benefits of DRA average out between users, hence
  - Fairness is achieved
- But how long does it take to average out?
  - Obvious implications for quality of service if the averaging takes too long

Ref:

Spectral Efficiency of Greedy, PFS and Round Robin

- PFS is an algorithm which attempts to achieve fairness. In this case, it is long term fairness.
- This can be seen to cost little in terms of spectral efficiency.
- Despite its debatable fairness, round robin clearly compares poorly in terms of spectral efficiency.



Ref:

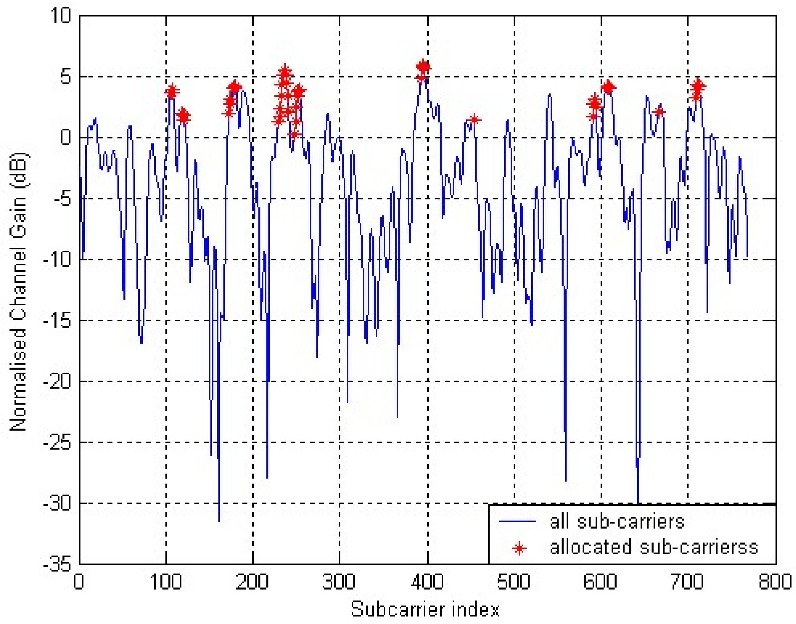
How can we make it fairer?

Dynamic Resource Allocation – Realistic Example (1)

- Dynamic Sub-Carrier Allocation in an Orthogonal Frequency Division Multiple Access system
- Consider a system with 768 sub-carriers (frequency ‘slots’)
- Allocate different sub-carriers to different links for multiple access
  - (O)FDMA
- For the case of 16 links we can allocate 48 sub-carriers to each

Ref:

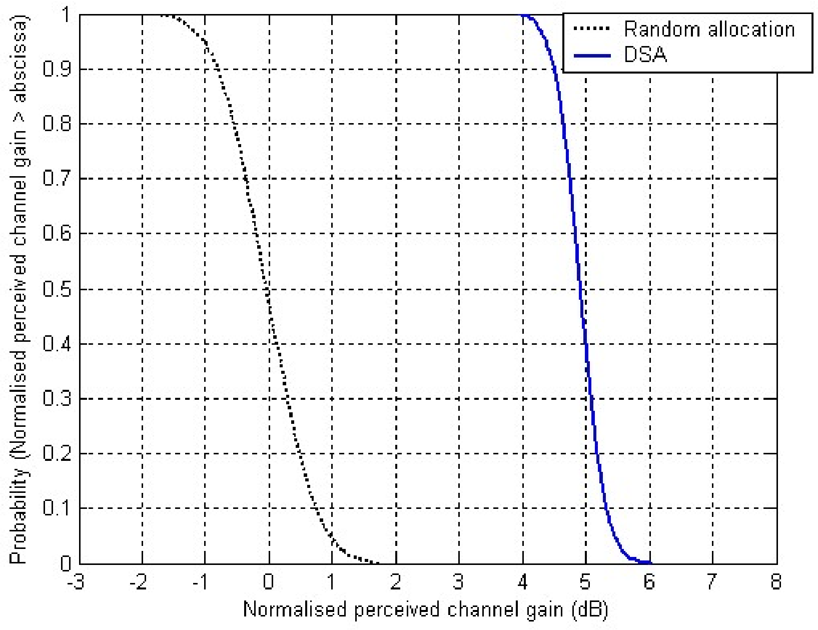
Dynamic Resource Allocation – Realistic Example (2)



- Shows:
  - Frequency response (signal quality) for all 768 sub-carriers for ONE user
  - 48 sub-carriers allocated sub-carriers
- For another link, the frequency response will (probably) be completely uncorrelated
- An algorithm can be employed to allocate the best combination of sub-carriers for this and all other links

Ref:

Dynamic Resource Allocation – Realistic Example (2)



- Statistical Comparison across many different links and channel instances
- Typically, the channel response is 5dB better on average and has less variance
- 5dB is a LOT!
- The gain is also fair across all links
- Source: CCR

Ref:

Dynamic Resource Allocation – What Cost?

- There is no such thing as a free lunch
- Multiuser Gain is achieved with no cost in terms coding, power, etc
- The ‘cost’ is that if the system is to dynamically allocate resources, it must notify all the devices in the communication system of changes to the allocation whenever they are made
  - This is an overhead – the control information occupies channel resources that would otherwise be used for data
  - The faster the allocation changes, the more the overhead
  - Ultimately, if the channel changes fast enough, there will be no benefit (or even a loss) from DRA

Dynamic Resource Allocation – Time Domain

- Time Domain DRA is quite feasible but introduces something of a conflict
- In order to get Multiuser Diversity in the time domain we need the users’ signal quality to vary in time in order to average out
- In order to ensure fairness for real time services, we probably need fairly rapid variation
- In order to minimise signalling cost, we need slow variation in time
- So if we do DRA in the time domain, we have conflicting needs for variation over time

Ref:

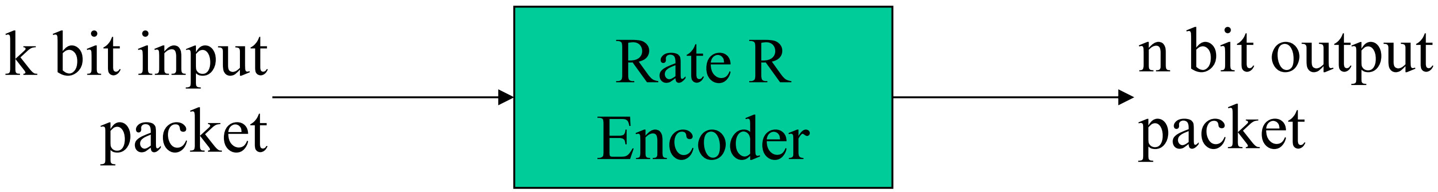
Dynamic Resource Allocation – Code Domain

- DRA in the code domain is not so easy
  - Note the absence of the code domain from the possible sources of diversity described earlier
- DRA has been proposed for UMTS HSDPA
  - HSDPA is a DS-CDMA system
  - However, DRA for HSDPA is proposed for use in the 'common channel' which is essentially TDMA
  - The term 'fade riding' is sometimes used in HSDPA
  - 'Fade Riding' is DRA in time

Ref:

Error Control

- Fundamentally, Error Control Strategies are based on the introduction of controlled redundancy into the data.
- The code rate, R, defines the ratio of input bits, k, to output bits, n, for a given encoder, hence R=k/n
  - Since redundancy is added R<1
  - Output data rate < Input data rate
- Thus, throughput is sacrificed in return for the ability to detect or correct errors



Ref: Lin & Costello

ARQ (1)

- Automatic Repeat reQuest (ARQ) exploits the redundancy to detect errors
  - Commonly, a Cyclic Redundancy Check Code is used
    - A CRC-N adds N bits to the data; $R=k/(k+N)$
- A protocol is employed which enables the destination node to inform the source node of the result of the error check either by:
  - Sending an acknowledgement (ACK)
  - Sending a negative acknowledgement (NACK)
  - The NACK may be implicit, i.e. if no ACK received, assume NACK
  - Given the relatively high likelyhood of errors in wireless communications, implicit ACKs are not a wise option!
- The source will then retransmit any packets believed to be in error

Ref: Lin & Costello

ARQ (2)

- Throughput is reduced:

$$f_{d,throughput} = f_{d,\mathrm{nominal}}\left(1-\sum_{r=1}^{\infty}\left(P_p\right)^r\right)$$

- However, if P_p is small, the first few terms of the summation dominate and:

$$f_{d,throughput} \rightarrow f_{d,\mathrm{nominal}}\left(1-P_p\right) \qquad \text{as} \qquad P_p \rightarrow 0$$

Ref: Lin & Costello

ARQ (3)

- In principle, ARQ guarantees near zero packet errors
  - If at first you don’t succeed, try,try,try…try again!
  - However, it is possible that errors go undetected
    - This becomes less likely as the code rate reduces
- The reduction in packet errors is achieved at the expense of increased packet delay
- The ‘round trip delay’ of successful packet transmission increases with the number of repeat transmissions required
- Ultimately, it may prove better to abandon a packet after a certain number of retries if it is delayed too long to be of use
  - This is again a function of the QoS Requirements of the application

Ref: Lin & Costello

ARQ (4)

- The mean total round trip delay of a packet is related to the mean round trip delay of a single transmission attempt and the number of retransmissions required:

$$D_{total,mean} \geq (r+1) D_{1,mean}$$

- If the round trip delay of a single packet transmission is constant, the statistics of the likely total round trip delay are trivial

ARQ (5)

- However, if the round trip delay per transmission attempt is not constant, the statistics of the total delay are non-trivial
- Variable round trip times combine with ARQ error control to cause delay jitter
- So ARQ degrades throughput and delay in order to improve error rates
- Given the harsh nature of wireless channels, ARQ is essential for all but the most error tolerant of applications

Ref: Lin & Costello

FEC (1)

- Forward Error Correction Coding (FEC) exploits redundancy to correct errors
- Given the received packet (which may contain errors) a FEC decoder has the task of choosing the most likely packet to have been input to the encoder
- Typically, lower rate codes can correct more errors
  - They can be compared by ‘coding gain’
    - How many fewer dBs of SNR required to achieve the same BER or PER with the code than without
  - Some codes are better than others and achieve more coding gain at a given rate
    - Often, this is at the expense of increased complexity

Ref: Lin & Costello

FEC (2)

- Thus a FEC code reduces the PER at the expense of also reducing throughput
- The effects on delay are minimal
- FEC cannot guarantee that the decoded packet is correct!
- There are lots of different FEC codes in common use: Hamming, Reed-Solomon, BCH, convolutional, Turbo, LDPC, etc

Ref: Lin & Costello

HARQ (1)

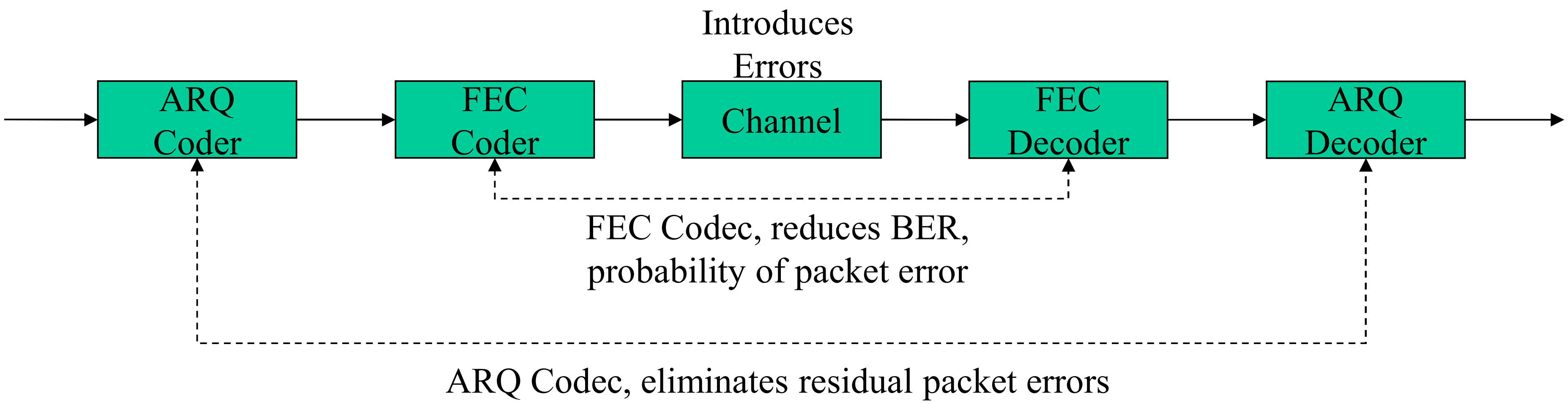
- ARQ and FEC both control errors
- ARQ can guarantee near zero error at the expense of throughput and delay
- FEC can reduce errors at the expense of throughput but with minimal implications for delay
- Often, the best result is achieved by combining an ARQ code with a FEC code
- This is sometimes referred to as Hybrid ARQ (HARQ)
- There are various clever forms of HARQ but the simplest is just a concatenation of two codecs

Ref: Lin & Costello

HARQ (2)

- Concatenation of codes results in net rate:

$$R_{net} = R_{ARQ} R_{FEC} = \frac{k_{ARQ} k_{FEC}}{n_{ARQ} n_{FEC}}$$



HARQ (3)

- ARQ codec ensures near zero errors
- FEC codec reduces the number of retransmissions required
- This is the simplest form of HARQ
- More advanced strategies involve:
  - Chase Combining
  - Incremental redundancy

Ref: Lin & Costello

Incremental Redundancy (1)

- Incremental Redundancy aims to transmit the minimal redundancy required to correct errors
- Consider a conventional FEC approach
- A binary word of k data bits is encoded to a binary word of n coded bits by adding n-k parity bits. (assume k=8 and that the k data bits appear as the first k bits of the coded word [the code is systematic]
- For a lower ratio of k/n:
  - the rate of the code will be lower
  - the spectral efficiency will be less
  - The Error correcting capability of the code will be higher

Ref: Lin & Costello

Incremental Redundancy (2)

- So for example:

Original data word:

d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8

Coded word for n=k=8, r=1 no error correction capability:

d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8

Coded word for n=12, r=2/3 some error correction possible

d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8	p_1	p_2	p_3	p_4

Coded word for n=16, r=1/2, increased error correction possible

d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8

Incremental Redundancy (3)

- But which code rate should be used?
- Errors are Random. It is unknown how many errors will occur
- Ideally the highest possible rate would be used but since this cannot be determined, an alternative approach is needed
- The principle of Incremental Redundancy is to first transmit a packet with a high rate code and then gradually lower the rate until error free communication of the packet is achieved

Incremental Redundancy (4)

- So the highest rate is transmitted first:

First Transmission

d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8

- If this data is not error free, redundancy is added by transmitting parity bits:

Second Transmission

p_1	p_2	p_3	p_4

- The receiver now has access to:

Data Available at Receiver

d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8	p_1	p_2	p_3	p_4

- It may be possible to determine the correct data from this

Ref: Lin & Costello

Incremental Redundancy (5)

- If not, more redundancy may be added

Third Transmission

p_5	p_6	p_7	p_8

- The receiver now has access to:

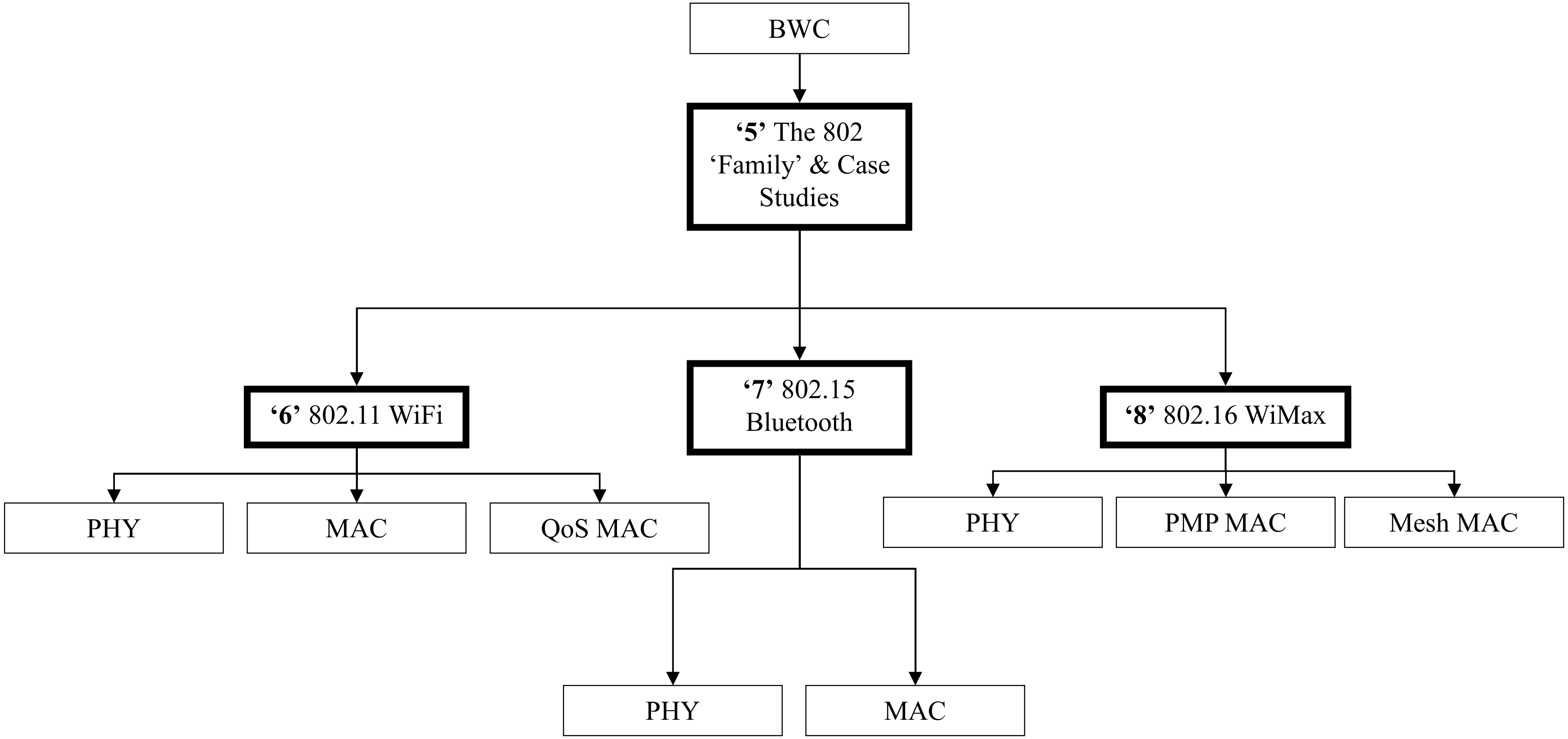
Data Available at Receiver

d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8

- It is more likely to be possible to determine the correct data from this
- If not, further redundancy may be added and so on…
- Ultimately, this will be limited by the range of code rates implemented but the principle remains the same

Ref: Lin & Costello

Course Roadmap



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