Topic 3a: The Physical Layer

Our goals:

- Understand physical channel fundamentals
  - Physical channels can carry data proportional to bandwidth and signal level and inverse proportion to noise level.
  - Modulation encodes digital data into an analogue channel.
  - Baseband vs. Broadband channel use.
  - Synchronous vs. Asynchronous.

Physical Channels / The Physical Layer

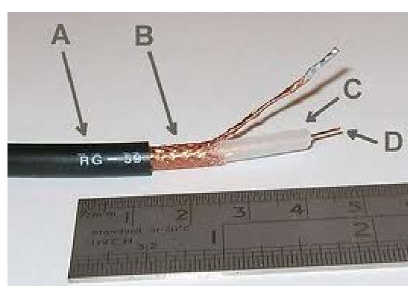
these example physical channels are also known as *Physical Media*

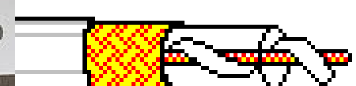
Twisted Pair (TP)

- two insulated copper wires
  - Category 3: traditional phone wires, 10 Mbps Ethernet
  - Category 8: 25Gbps Ethernet
- Shielded (STP)
- Unshielded (UTP)

Coaxial cable:

- two concentric copper conductors
- often bi-directional
- baseband:
  - single channel on cable
  - eg. legacy Ethernet
- broadband:
  - multiple channels on cable
  - HFC (Hybrid Fiber Coax)





Fiber optic cable:

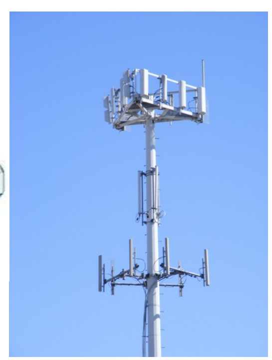
- point-to-point transmission
- (10's-100's Gbps)
- low error rate
- immune to electromagnetic noise

Another important physical medium: Radio

- Bidirectional and multiple access
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

Radio link types:

- terrestrial microwave
  - e.g. 90 Mbps channels
- LAN (e.g., WiFi)
  - 11Mbps, 54 Mbps, 600 Mbps
- wide-area (e.g., cellular)
  - 5G cellular: ~ 40 Mbps - 10Gbps
- satellite
  - 27-50MHz typical bandwidth
  - geosynchronous versus low altitude
  - For geosync - 270 msec end-end delay to orbit



Physical Channel Characteristics - Fundamental Limits -

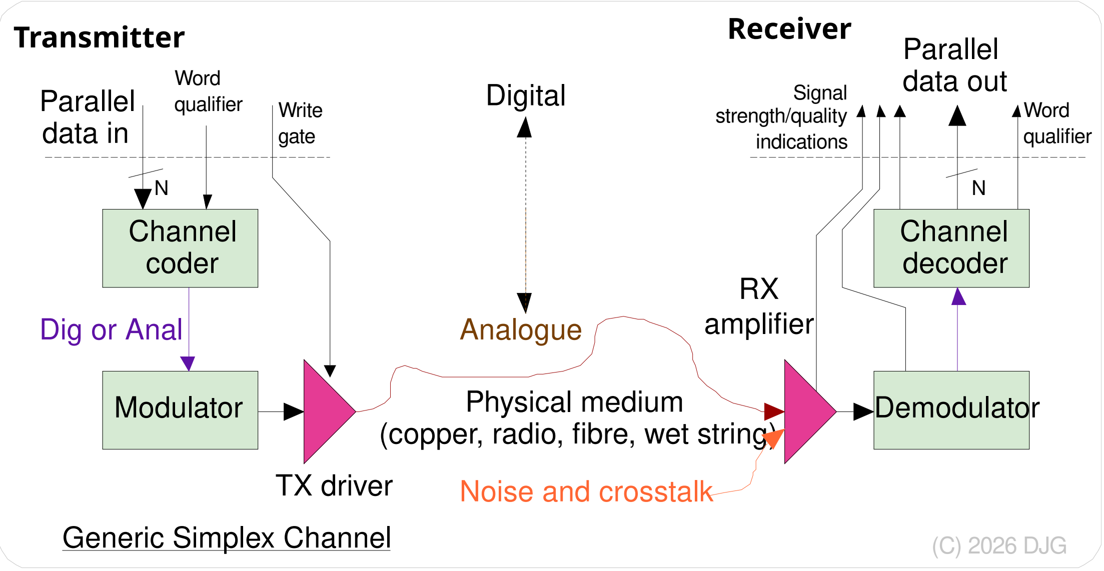
- **Delay**: speed-of-light in medium and distance travelled
- **Fidelity**: signal-to-noise ratio (SNR)
- **Bandwidth**: a measure of the range of frequencies of sinusoidal signal that channel supports

Bandwidth:

- E.g., a channel that supports sinusoids from 1 MHz to 1.1 MHz has a bandwidth of 100 KHz
- “supports” in this context means “comes out the other end of the channel”
- some frequencies supported better than others
- analysing what happens to an arbitrary waveform is done by examining what happens to its component sinusoids → Fourier analysis

Bandwidth and SNR are our key resources.

Basic Channel (L1) Structure



L1 Physical layer - conveys bits

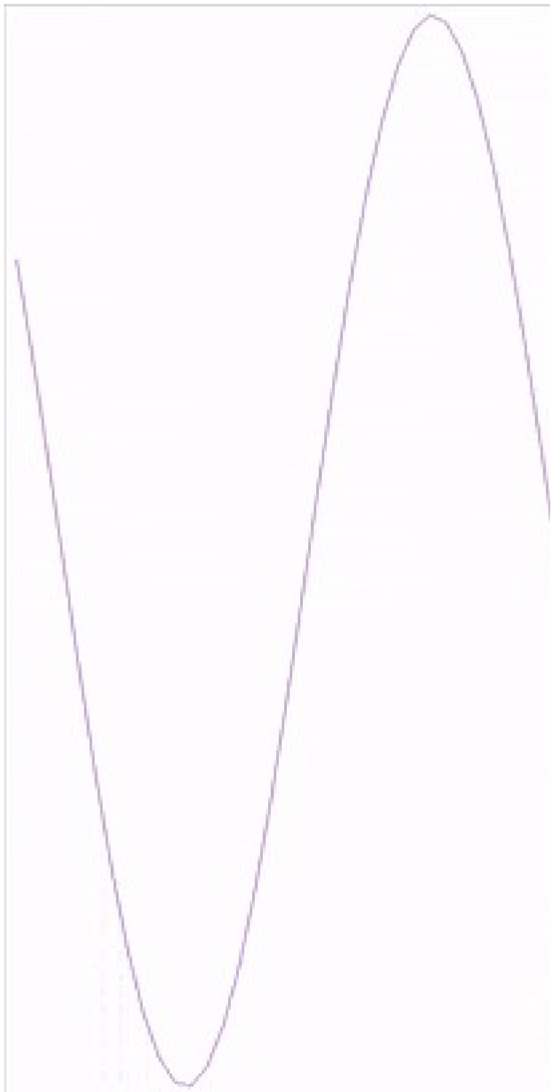
L2 Data link layer – understands framing, addresses and MAC

The distinction is often not entirely clear

System can work better if there is no clear boundary

Making the decision ONCE about what a packet contains is always better
In information-theory terms.

Analogue meets digital



Square waves have high frequency components in them

Channels attenuate frequencies irregularly:
changing the shape of the signal

Receiver signal is related to the transmitted signal + noise.

Noise may be systematic or random.

Systematic noise from interfering equipment
can in principle be eliminated (not always convenient).

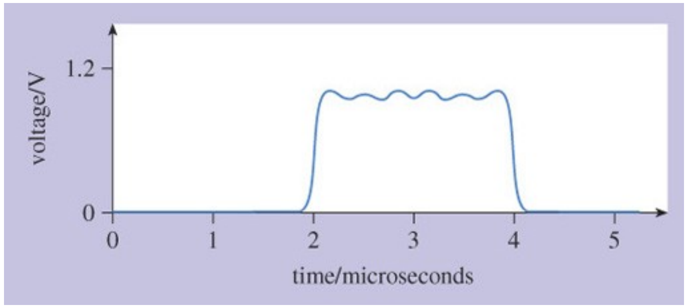
Random noise caused by thermal vibration (thermal noise) and often mostly depends on the temperature of the receiver.

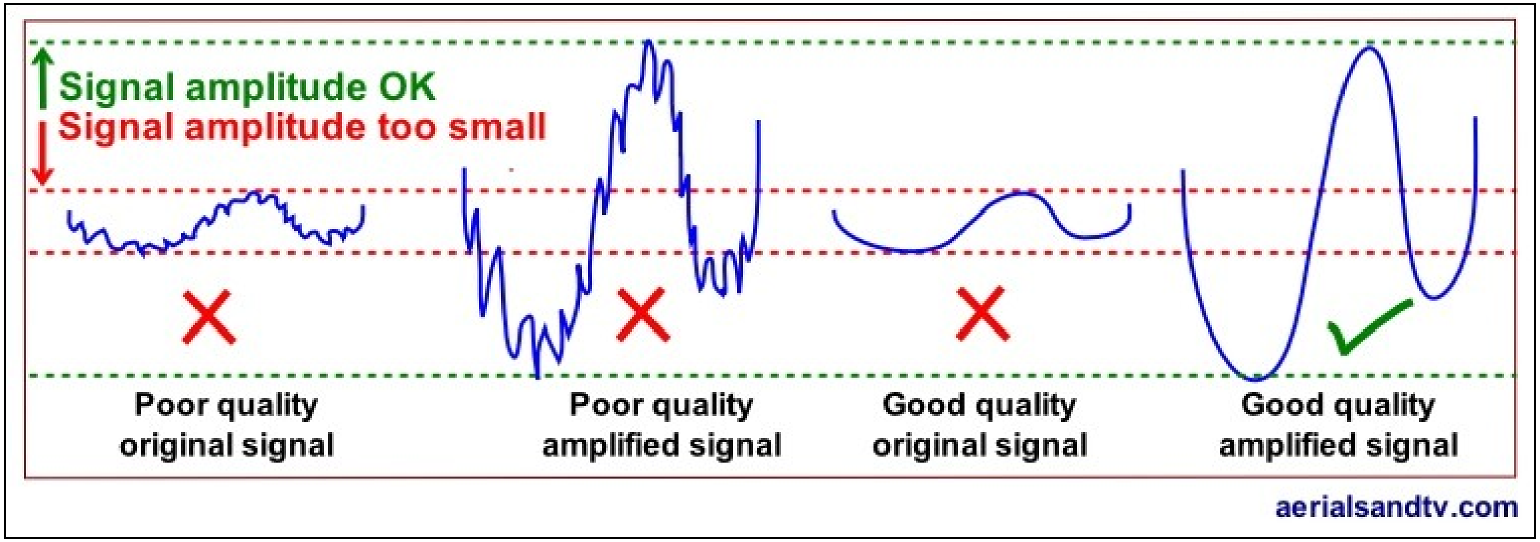
“White” noise is evenly distributed across frequencies.

Signal-to-noise ratio *S/N:* more distance, weaker signal, comparatively more noise.

Noise: Enemy of Communications

Attenuation, External Noise,
Systematic, non-systematic,
digitization, interference, reflection, ….





Link Power Budget

- **Launch power** - the peak energy emitted per second (Watts).
- **Medium loss** - how much the physical medium attenuates the signal, generally by converting it to heat and typically expressed per unit length.
- **Scattering loss** - how much of the launched power 'hits' the receiver assuming no medium loss.
- **Receiver self-noise** - the noise generated inside the receiver. For most modulation schemes, the received far-end signal must be several dB higher than the receiver-self noise, effectively limiting the length of a practical channel.
  - can be minimised by cooling the receiver, as used in radio telescopes.
- **Near-end crosstalk (NEXT)** - for a duplex system, how much of the locally transmitted power finds its way into the local receiver, acting like another form of noise,
  - potential to overcome the far-end signal.
  - can sometimes be cancelled out by subtraction of a filtered version of the transmitted signal.
- **Pickup noise** - signals from other systems and energy sources that find their way into the receiver.
  - generally be minimised by Faraday screening (put a metal box around the sensitive electronics
  - boxes also restrict unintentional emissions, as required by law.

Bandwidth and Signal-to-Noise

What's better: high bandwidth or low signal to noise?

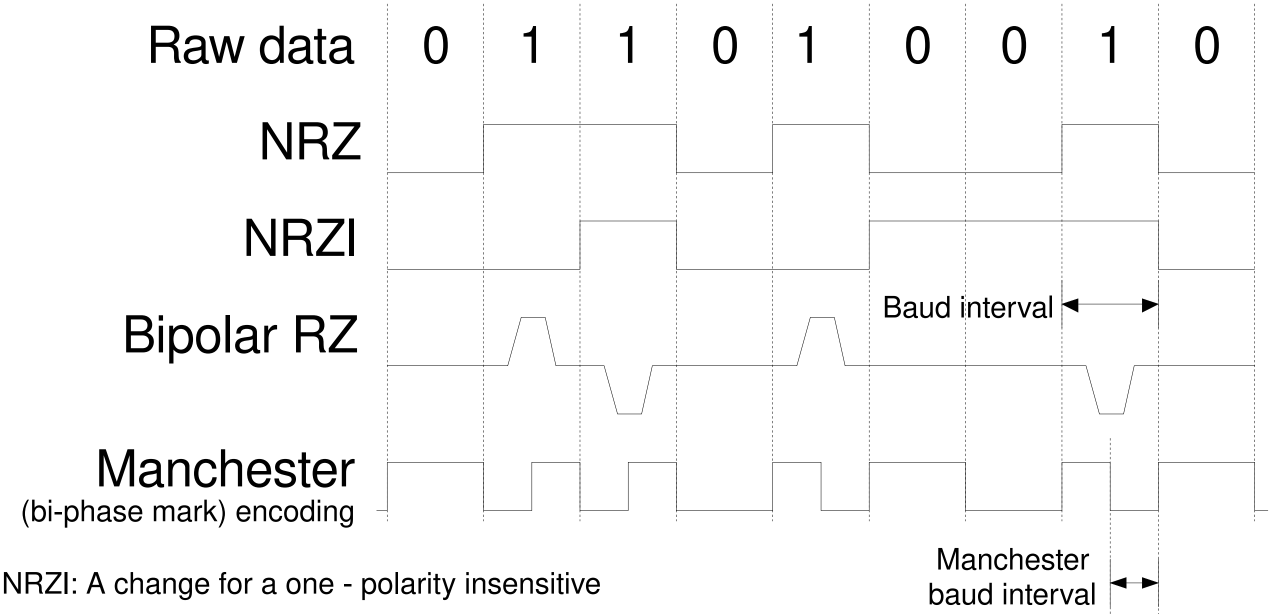
- channels subject to white noise have information capacity *C* measured in bits per second, of a channel

$$C = Blog_2(1 + S/N)$$

B is the bandwidth of the channel *S/N* is the ratio of received signal power to received noise power.

- Channels with any signal have non-zero information capacity
- Channel with signal-to-noise ratio of unity have an information capacity in bps equal to its bandwidth in Hertz.
- A fundamental limit, regardless of improvements in modulation or FEC.

Digital Channel Modulation



NRZI: A change for a one - polarity insensitive

Bipolar - alternate polarity pulses for 1's

Bi-phase mark: a change on every bit boundary. A change inside the bit cell denotes a 1.

Properties:

Bipolar and Manchester have no DC content.
Manchester has 1/2 bit per baud, but guarantees a very high density of transitions.
Bipolar 'wastes' signal power?
Bipolar HDB3 uses violations (not shown) of alternation rule to ensure density,
but self-synchronous scrambling is typically used too.

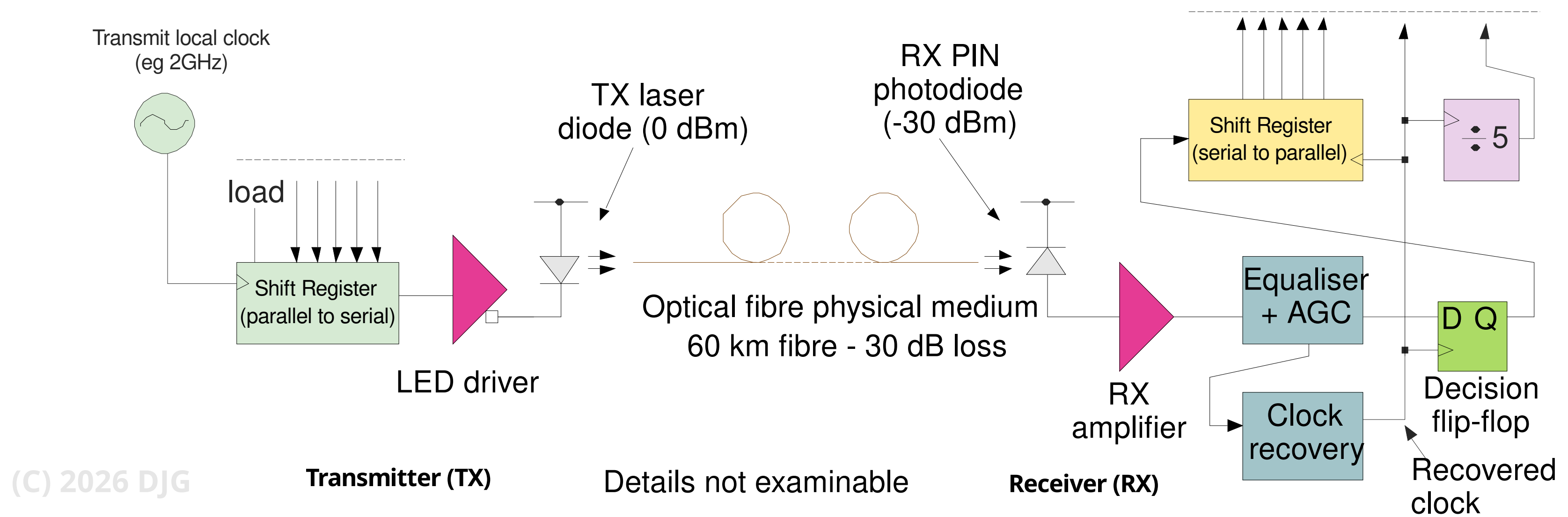
- Baud rate, R, is the rate at which symbols can be transmitted.
- Data rate, D (or bit rate), is the equivalent number of binary digits conveyed.
- Eg. 4-level signal gives 2 bits per baud interval

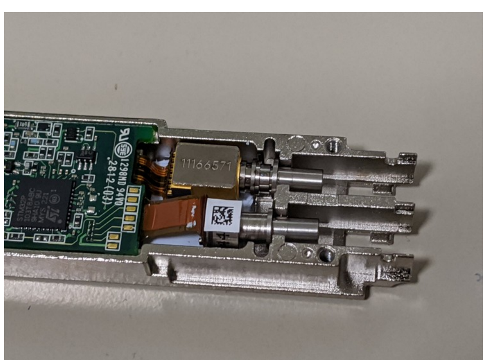
$$D = 2R$$

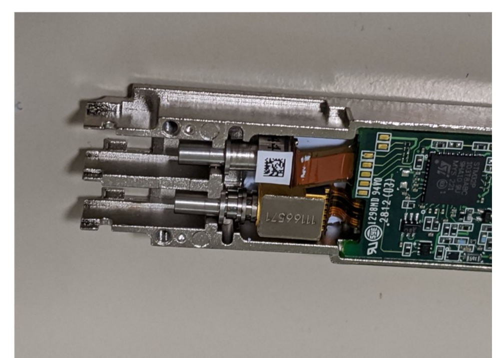
These are modulation schemes from the 1950's. Modern are far more complex!

Optical Fibre System

Simplex baseband channel - variations for a fibre-optic binary NRZ channel block diagram







Optical Fibre Power Budget

Simplex link example:

- Transmit power 10 dBm (ie 10 mW).
- Scattering loss (some light not entering the fibre) but accounted within the 10 dBm.
- Receiver sensitivity before self-noise dominates -20 dBm
- Fibre loss (monomode) 0.5 dB/km
  - Tight bending or attempts at tapping it can cause greater losses.
  - Optical connectors lossy (2 dB), so fusion splicing preferred as far as practical.
- Zero near-end cross talk (NEXT) (unless optical directional couplers are used for duplex operation on a single fibre. These couplers have an intrinsic 3 dB insertion loss and some excess loss. They can be bulky, not very directional and so on.
- Pick-up is negligible in all cases

Max length is 60 km from these figures?

Passive optical networks (PONs) also widely used (half duplex)

Further Common Channels

0. Fibre

1. Asynchronous RS232

2. Block-coded (synchronous, baseband)

3. QPSK radio (synchronous, broadband)

4. OFDM (synchronous, FDM internally, baseband or broadband)

5. CDMA (synchronous, code-division multiplexing (CDM)

Also: Scrambling for security, transitions and whiteness – (likely not lectured 2526)

Asynchronous Example: RS232

UART data configurations
and data format (from MSD).

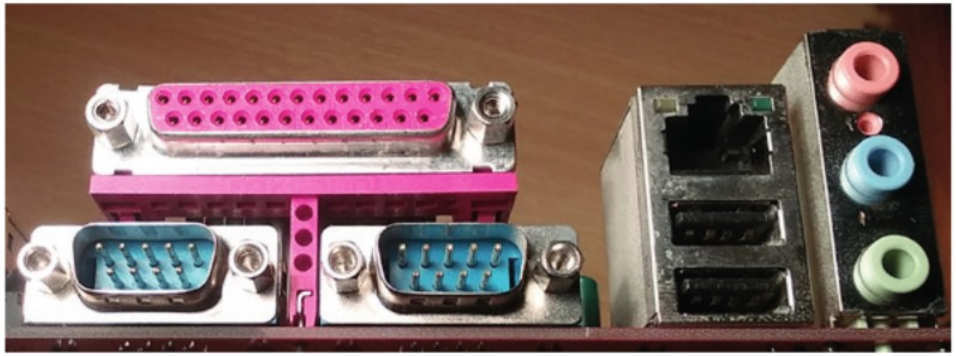


Figure 2.29 Typical I/O ports. Shown are two serial ports, one parallel port, one Ethernet port, two USB ports and three audio ports

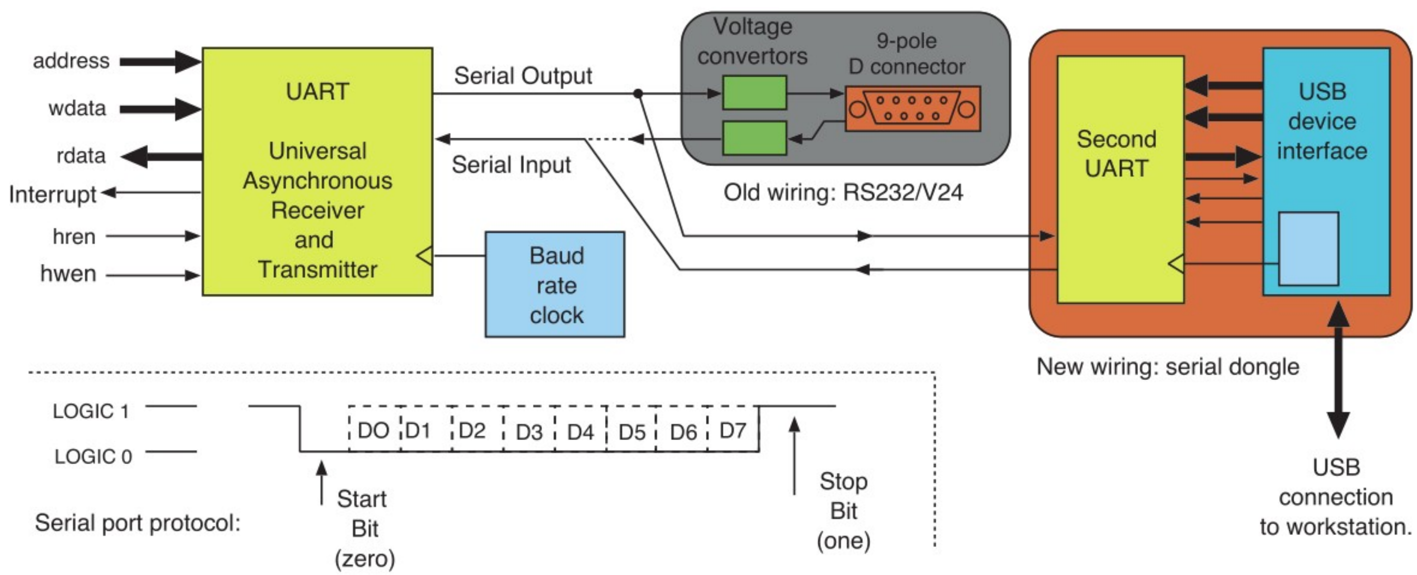


Figure 2.30 Two typical configurations for a serial port using a UART. Inset: Serial port timing diagram. The old wiring to a D9 connector for an RS-232 port is today often replaced with a very short connection to a second UART inside a USB dongle for connecting to a laptop

Asynchronous

Transmission is sporadic, divided into frames

- Transmitter and receiver have oscillators which are close in frequency producing TX clock and TX clock
- Receiver synchronises the phase of its RX sampling with TX by looking at one or more bit transitions.
- RX clock drifts with respect to TX, but stays within a fraction of a baud throughout the duration of a frame.
- Transmission time (frame length) is limited by accuracy of oscillators.

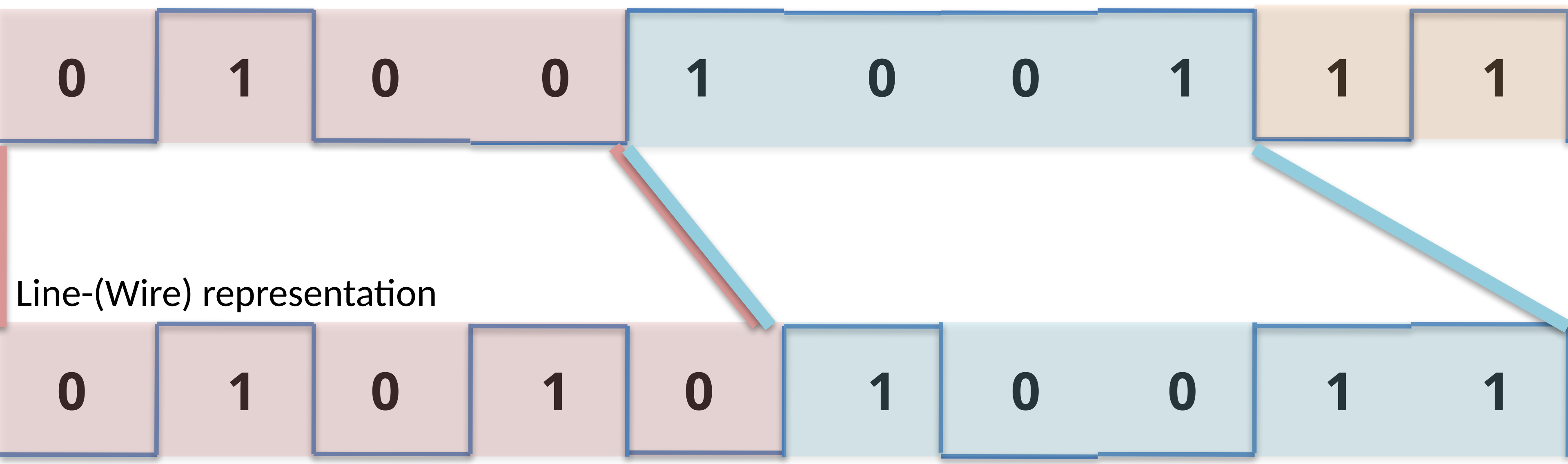
Synchronous

Transmission is continuous

- Receiver continually adjusts its frequency to track timing information inherent in the incoming signal or a global master clock (eg Sonet/SDH).
- Requires frequent bit transitions to recover clock.
- Clock recovery: A phase-locked loop tracks where clock edges nominally occur, correcting itself slightly when wrong.

Line Coding – Block Coding Example

Data to send



Name	4b	5b	Description
0	0000	11110	hex data 0
1	0001	01001	hex data 1
2	0010	10100	hex data 2
3	0011	10101	hex data 3
4	0100	01010	hex data 4
5	0101	01011	hex data 5
6	0110	01110	hex data 6
7	0111	01111	hex data 7
8		1000	10010 hex data 8
9		1001	10011 hex data 9
A	1010	10110	hex data A
B	1011	10111	hex data B
C	1100	11010	hex data C
D	1101	11011	hex data D
E	1110	11100	hex data E
F	1111	11101	hex data F

Name	4b	5b	Description
Q	-NONE-	00000	Quiet
I	-NONE-	11111	Idle
J	-NONE-	11000	SSD #1
K	-NONE-	10001	SSD #2
T	-NONE-	01101	ESD #1
R	-NONE-	00111	ESD #2
H	-NONE-	00100	Halt

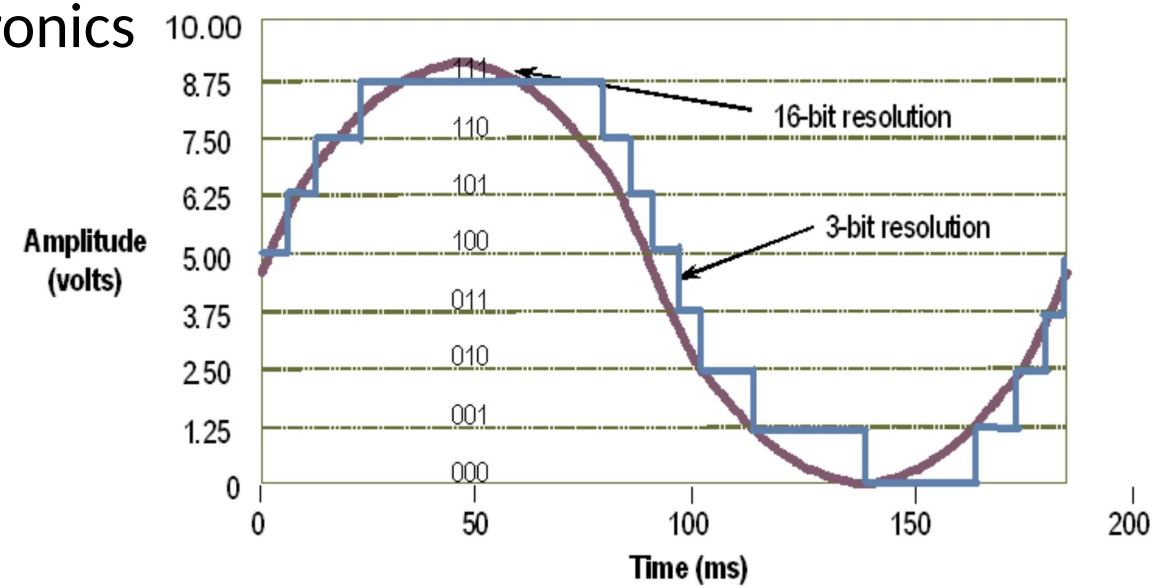
Block coding transfers data with a fixed overhead: 20% less information per Baud in the case of 4B/5B

So to send data at 100Mbps; the line rate (the Baud rate) must be 125Mbps.

1Gbps uses an 8b/10b codec; encoding entire bytes at a time but with 25% overhead

DtoA (DAC) and AtoC (ADC)

Recall from Digital Electronics



Conversion errors can occur in both directions

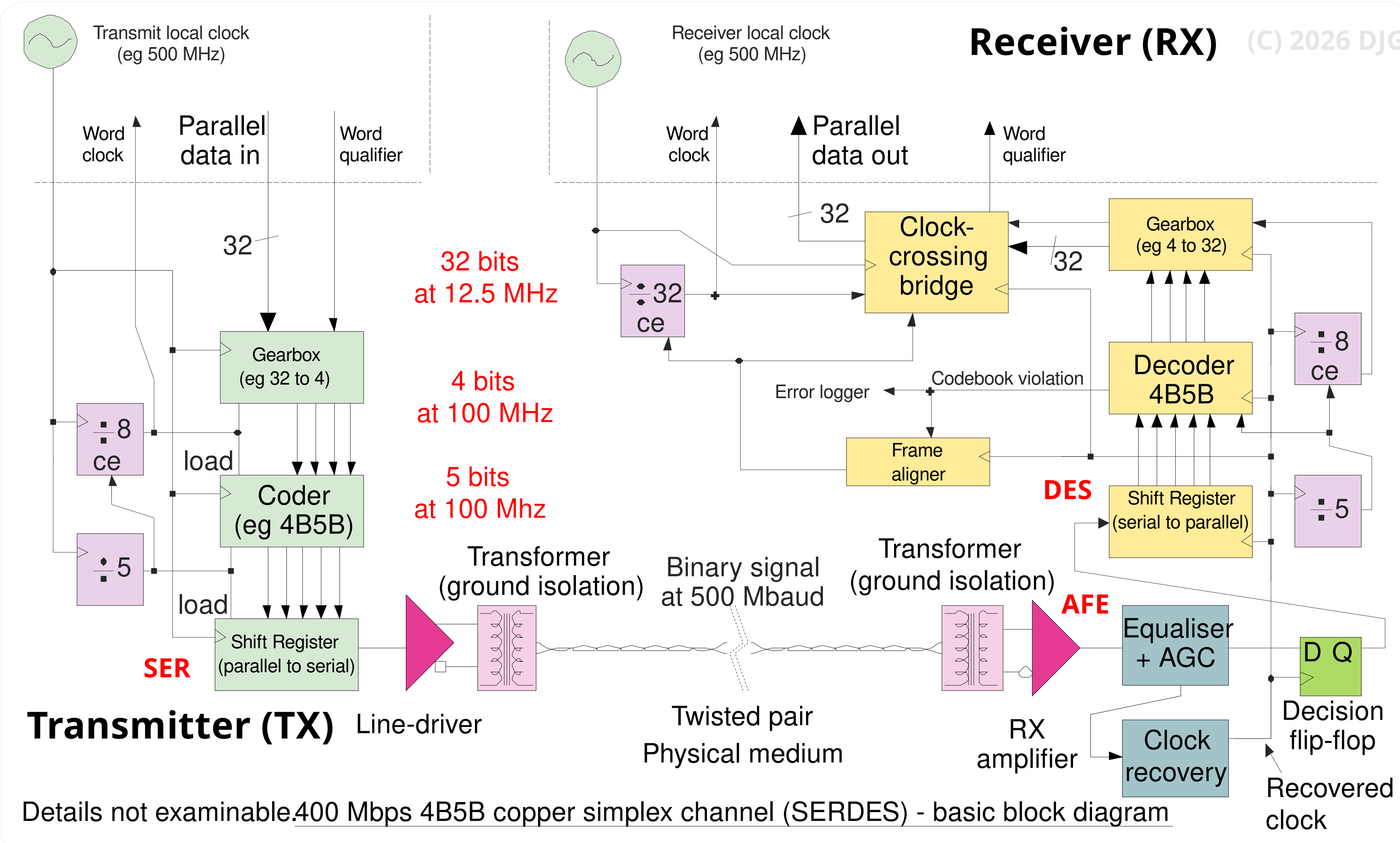
e.g.

Noise leads to incorrect digitization

Insufficient digitization resolution leads to information loss

Our ‘decision flip-flop’ was a 1-bit ADC

Line Coding – Block Coding Detail



Generally (not shown), an NRZI encoder is added at the transmitter, with a matching decoder at the receiver. The selection of appropriate code words should then be biased towards those with the most ones and the fewest consecutive zeroes, since they provided the greatest transition density.

Copper (Coax/Twisted-pair) - Power Budget

Transmit power might be about 0 dBm (eg 1 volt peak-to-peak, which in rms terms, is 1.3 mW given a 100 ohm characteristic impedance).

All of the transmitted power enters the cable, so there is no **scattering loss,** apart from a small amount of radiation from unbalance in the cable twisting.

The **receiver sensitivity** (before self-noise dominates) might be 10 mV peak-to-peak, which is 40dB less, or roughly -40 dBm.

Cable **path loss** might be about 0.2 dB/m, giving a maximum length restriction of 200 metres.

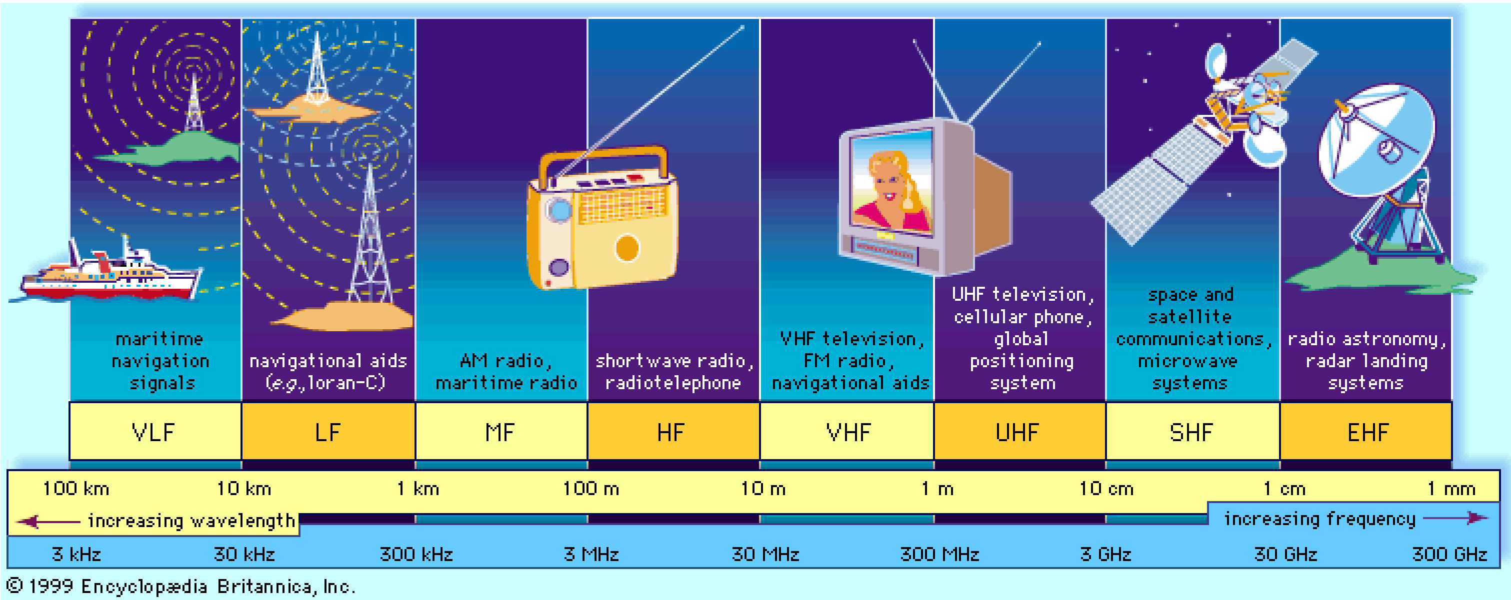
The **near-end cross talk** (NEXT) will be about -30 dB in many cases, so the full length cannot be used in duplex cables:

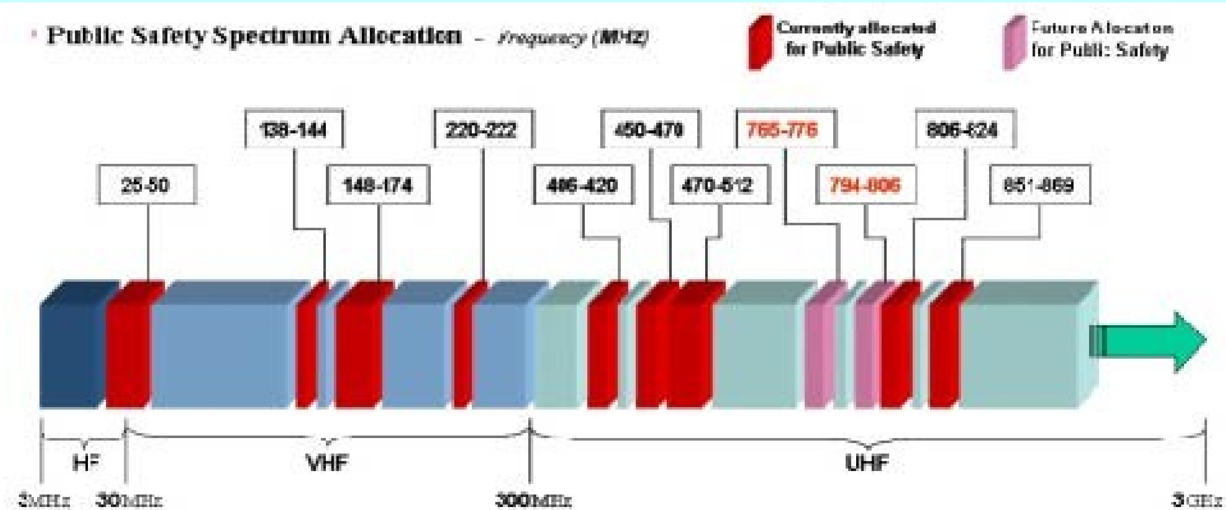
- Perhaps cancellation of the known-to-be-transmitted signal can give another 10 dB of margin
- But problematic if multiple pairs in the same cable are being driven at once, as in gigabit Ethernet.
- High quality cabling have a tight NEXT specification (eg -44 dB for CAT 6), which may make the channel not limited by NEXT.

Pick-up should be negligible in most cases, especially if shielded twisted pair or coax is being used.

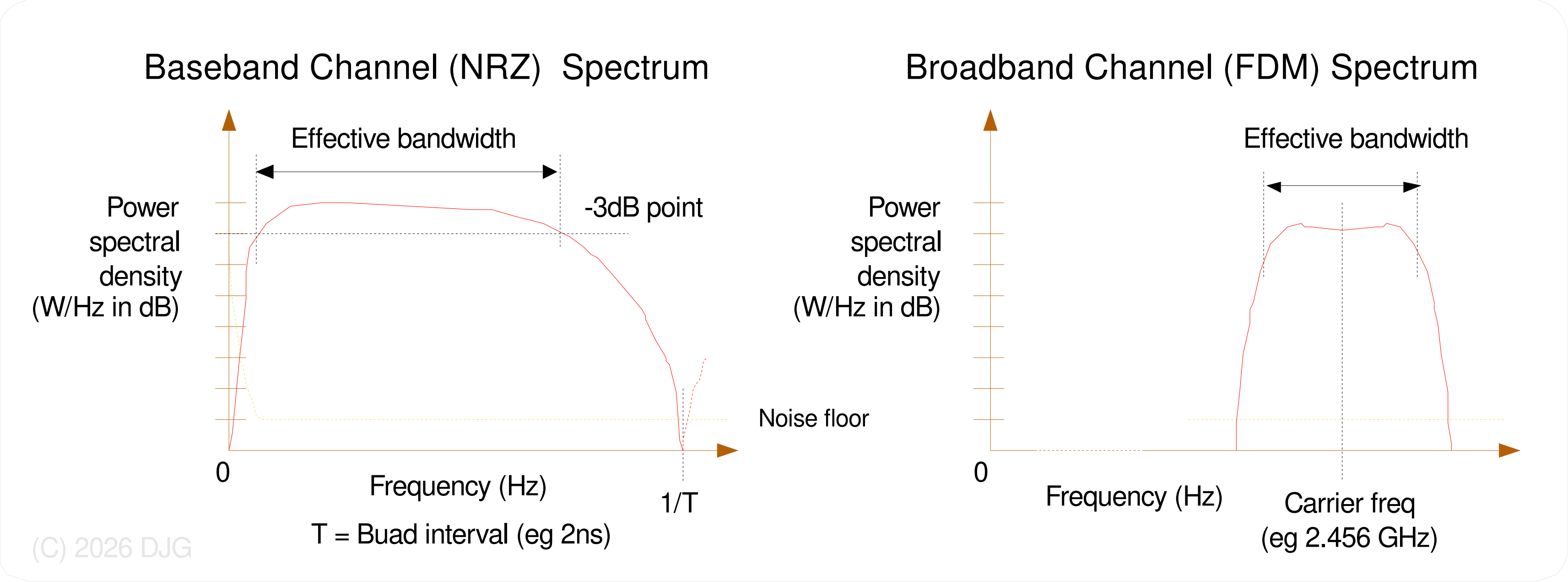
- But if operating next to an electric blast furnace or
- EMP bomb testing range, there could be problems. [Optical fibre does not suffer from that!]

The Radio (or Wireless) Spectrum (or Ether)





Baseband vs Broadband



NRZ data is a baseband signal.

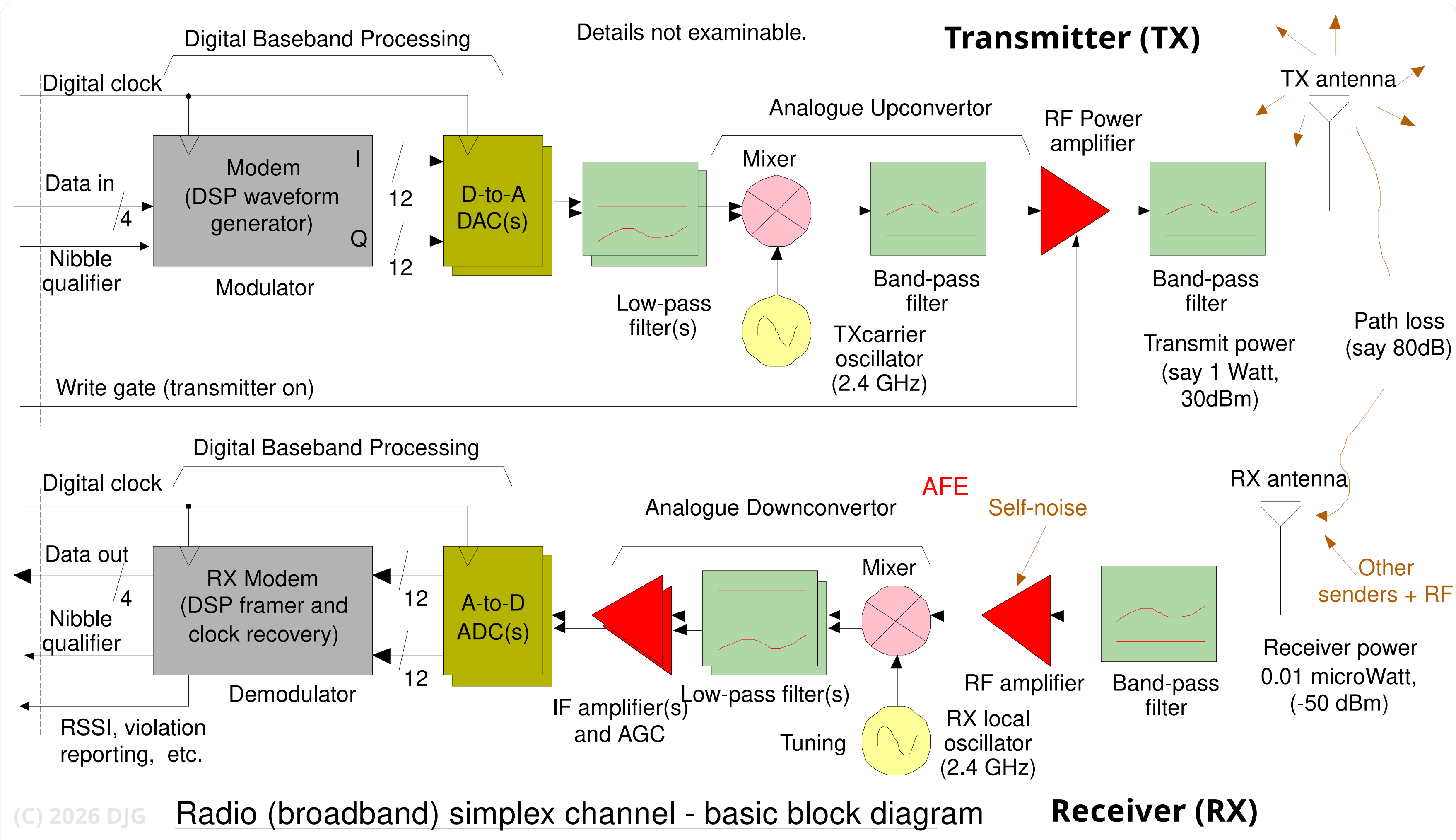
NRZ has a sync (sin(x)/x) spectrum with the first null at 1/T [T is Baud interval]

Removing the DC and low-frequency parts produces another null at 0.

A baseband signal is up-converted to a broadband signal using hetrodyning (multiplying with a sine wave carrier)

```
sin(a) x sin (b) = 1/2 cos(a-b) - 1/2 cos(a+b)
```

QPSK Radio Link Basic Structure



Quadrature phase-shift keying – QPSK – sidebands dissimilar

Radio Link Power Budget Example

Transmit power 10 dBm (eg 10 mW)   (but mobile phones use up to 4W or 36 dBm). Too much causes fright/frying.

Scattering loss: With a simple antenna system, radio waves go out in all directions (isotropically) and scattering loss is the dominant form of loss.

- For isotropic emissions, the inverse square law applies.
- For directional antenna, such as a microwave dish, far less, since the radio waves are only sent in the intended direction.
- Pickup noise is greatly reduced by directional antenna (dish or phased array)

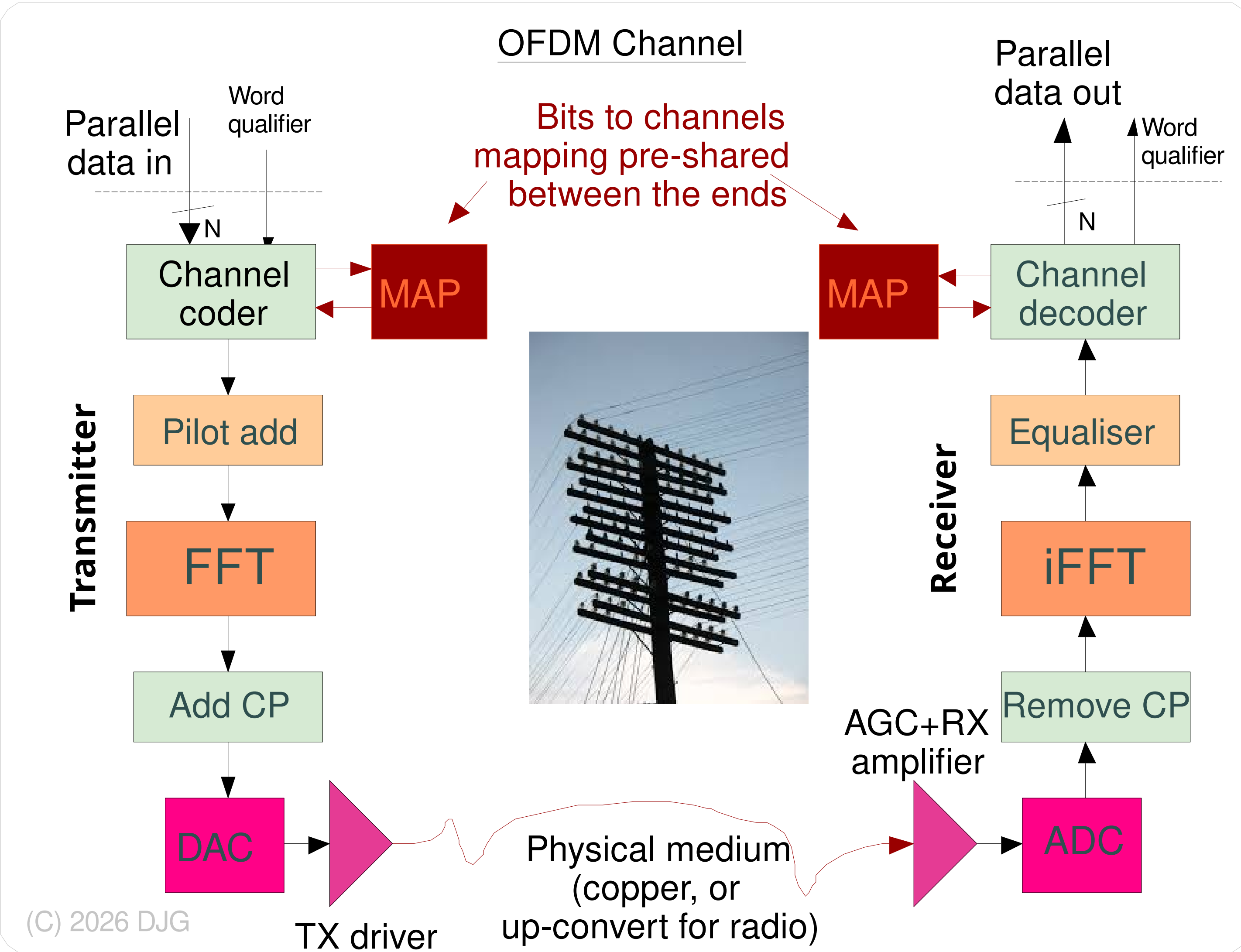
Receiver sensitivity before self-noise dominates might be 10uV (or -80 dBm - please do exact sum here DJG).

Path loss (attenuation) depends on the atmosphere, but is zero in outer space and a few tens of dB during rain storms

Pick-up is generally a big problem for radio systems, especially from faulty or unlicensed equipment.

I purchased a battery charger from Amazon that was CE-marked but which completely obliterated BBC Radio 2 nearby.

Orthogonal Frequency Division Multiplexing



Prototype ADSL modem (DJG 1995)

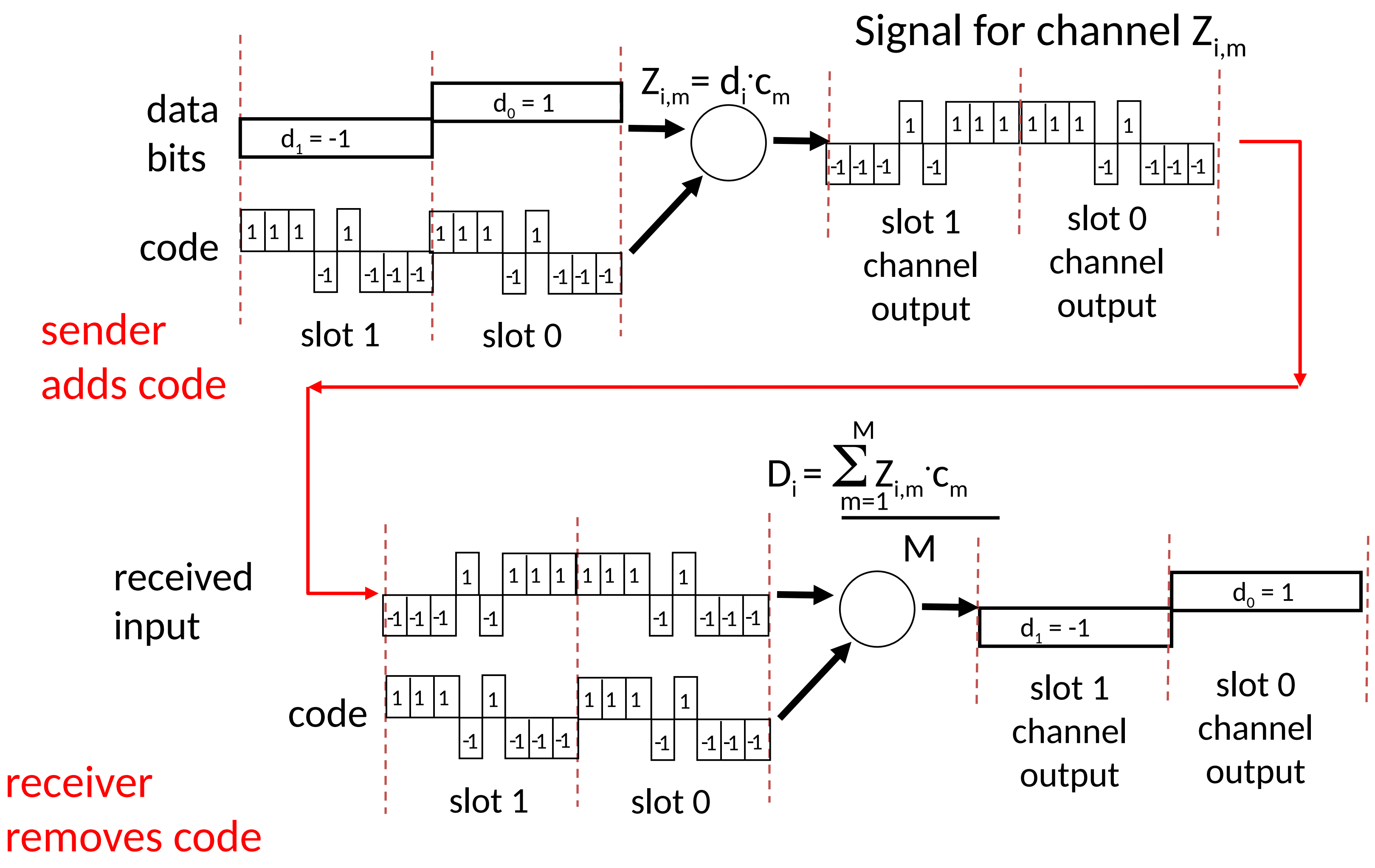
OFDM

- Suitable for channels with very uneven phase and frequency responses.
- Widely used in residential ADSL
- Widely used in radio systems (where it is properly termed broadband), as it is able to handle multi-paths constructively and keep up with slowly changing patterns of attenuation (and shifting phases) owing to movement.
- Uses a large number of FDM bands each at a very low baud rate (such as 8 kbaud).
- Typically 100 to 200 bands
- For example: 100 bands with 32 levels at 8 kbaud gives 4 Mbps.
- Based on FFT (fast Fourier transform) at the sender with its inverse at the receiver.

Code Division Multiple Access (CDMA) (not to be confused with CSMA!)

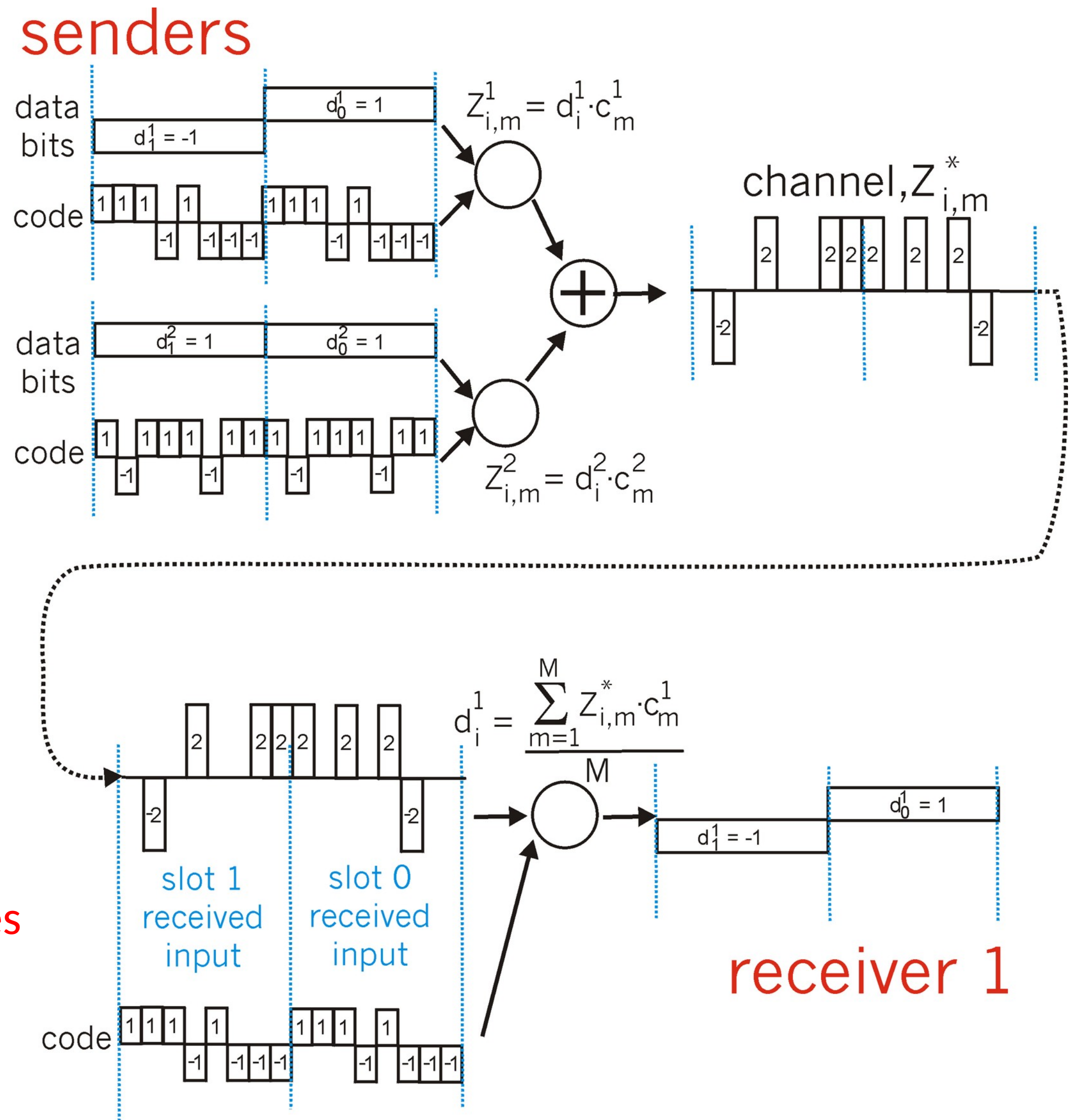
- Used in several wireless broadcast channel (cellular, satellite, etc) standards
- Unique “code” assigned to each sender.
- All senders share same frequency, but each has its own “chipping” sequence generated from the code , used to encode their baseband waveform.
- *encoded signal* = (original data) XOR (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence
- Allows multiple users to “coexist” and transmit simultaneously with minimal interference (if codes are “orthogonal”)

CDMA Encode/Decode



CDMA: two-sender interference

Each sender adds a ***unique*** code



Sender one demodulates using its ***unique*** code

Scrambling – for security

- Fragments a message (in the time or frequency domain, or both).
- Systematically permutes the fragments.
- The resulting signal is unintelligible to humans.
- Corresponding de-scrambler must have knowledge of the scrambling order (a shared secret key).

Turing built such a scrambler using valves. Modern encryption is much better.

Line Coding Scrambling – for security

Step 1

....G8wDFrB
EAFDSWbzQ7
BW2fbdTqeT
ImrukTYwQY
ndYdKb4....

REPLICATE SECURELY

Scrambling Sequence

DISTRIBUTE SECURELY

Step 2

Scrambling Sequence

Scrambling Sequence

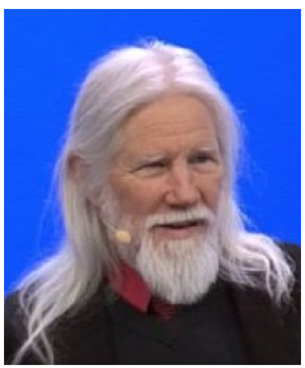
Message

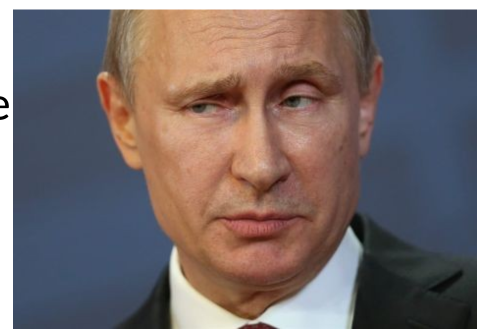
Communications Channel

Message

Message XOR Sequence

Message XOR Sequence





Step 3 Don't ever reuse Scrambling sequence, ever. <<< **this is quite important**

Whitfield Diffie

Martin Hellman

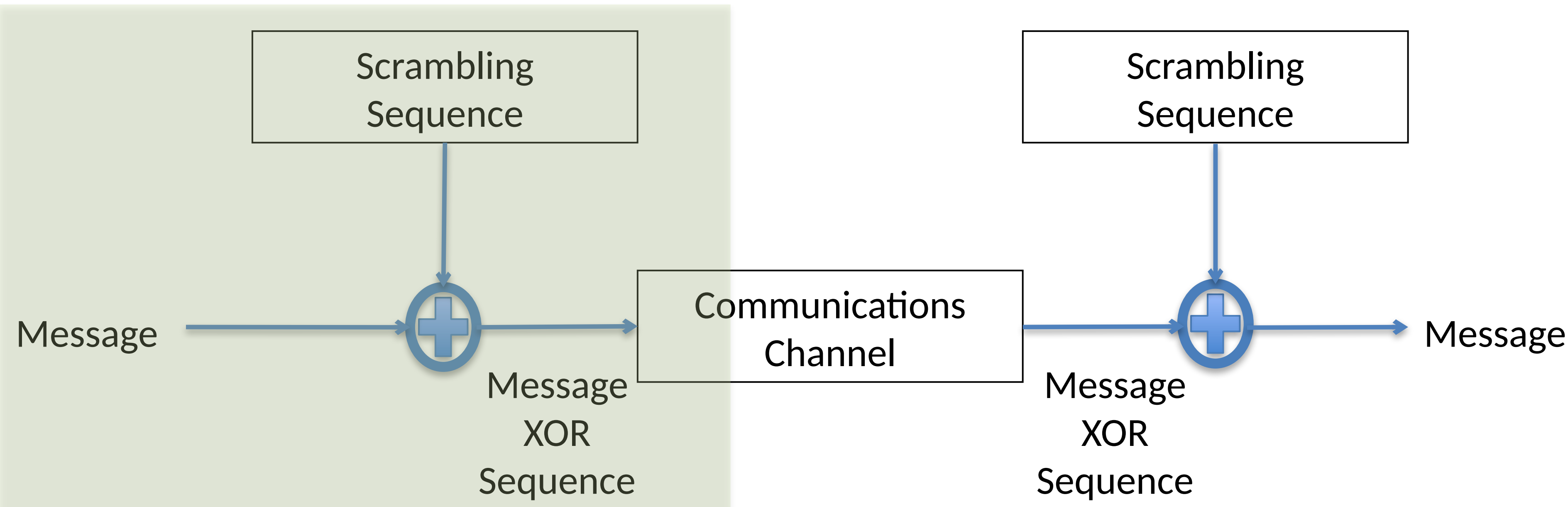
This slide onwards likely not lectured by DJG 2526

Whitening (Self-synchronous) Scramber

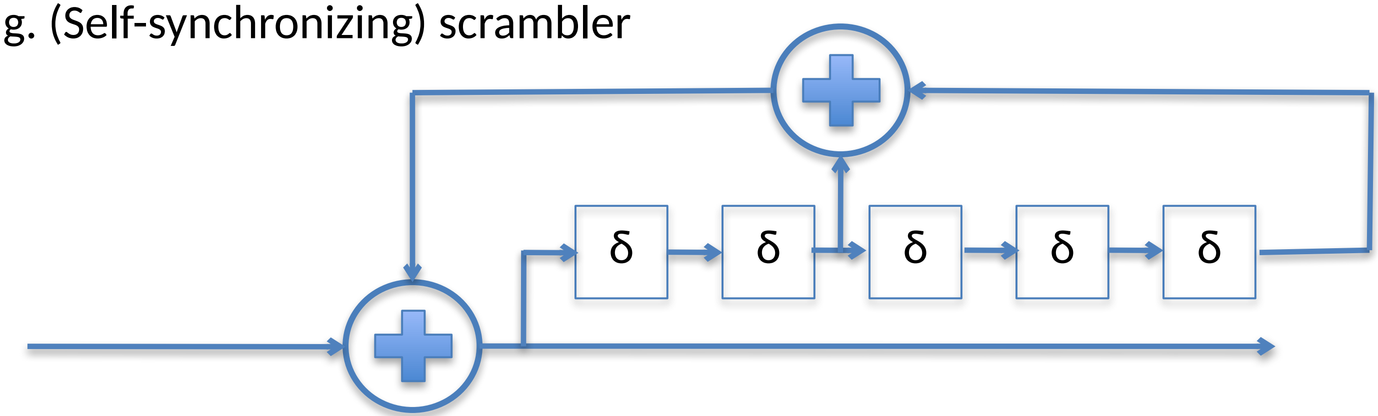
- Uses a fixed, public scrambling order.
- NRZ bits of channel data exclusive-or'd with some set of recently sent bits.
- Tends to eliminate runs of successive correlated or same-value bits, increasing average transition density, making clock recovery easier.
- Works well for digital audio in telephone systems (PCM pulse-code modulation), where there very long runs of zeroes common.
- For general digital applications, a low probability that the data correlates badly with the fixed scrambling order! Could be locally worse for clock recovery.

This has no overhead in terms of bits per baud.

Line Scrambling– for 'whitening' (not secrecy)



e.g. (Self-synchronizing) scrambler



Hybrids commonly used (layers again)

…100111101101010001000101100111010001010010110101001001110101110100…

…10011110110101000101000101100111010001010010110101001001110101110100…

Inserted bits marking "start of frame/block/sequence"

Scramble / Transmit / Unscramble

…0100010110011101000101001011010100100111010111010010010111011101111000…

Identify (and remove) "start of frame/block/sequence"
This gives you the Byte-delineations for *free*

64b/66b combines a scrambler and a framer. The start of frame is a pair of bits 01 or 10: 01 means "this frame is data" 10 means "this frame contains data and control" – control could be configuration information, length of encoded data or simply "this line is idle" (no data at all)

Hybrid Example

- Example: mobile phone radio link:
  - Block code (using table-lookup)
    - fixed overhead, inline control signals
  - Scramble (using shift registers)
    - No overhead
  - OFDM (Orthogonal FDM)
    - Copes well with multi-path
  - CDMA (Code Division Multiple Access)
    - Carrier frequency rapidly hops, mostly avoiding noise sources and other users.

Ideally, demodulate all layers at once, for maximum noise rejection (best decision).