University of Glasgow

Data Link Layer (1)

Networked Systems 3
Lecture 6

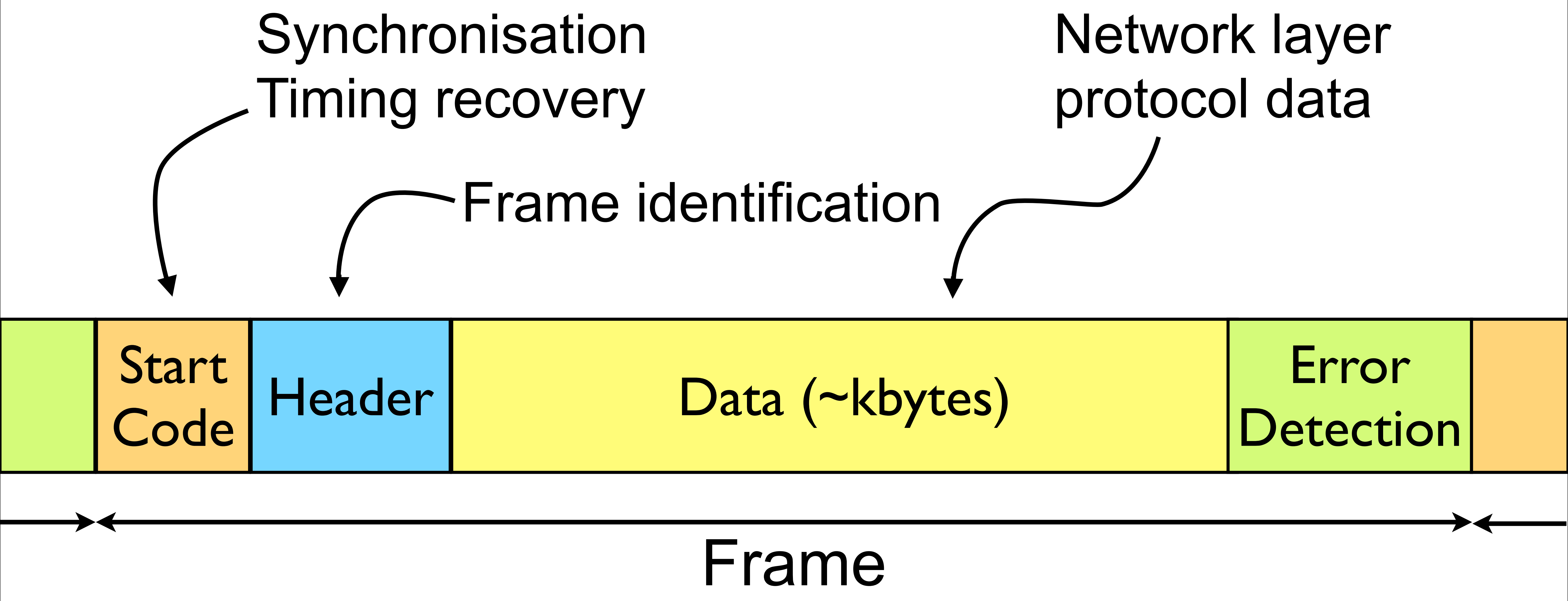
Purpose of Data Link Layer

- Arbitrate access to the physical layer
    - Structure and frame the raw bits
    - Provide flow control
    - Detect and correct bit errors
    - Perform media access control
- Turn the raw bit stream into a structured communications channel

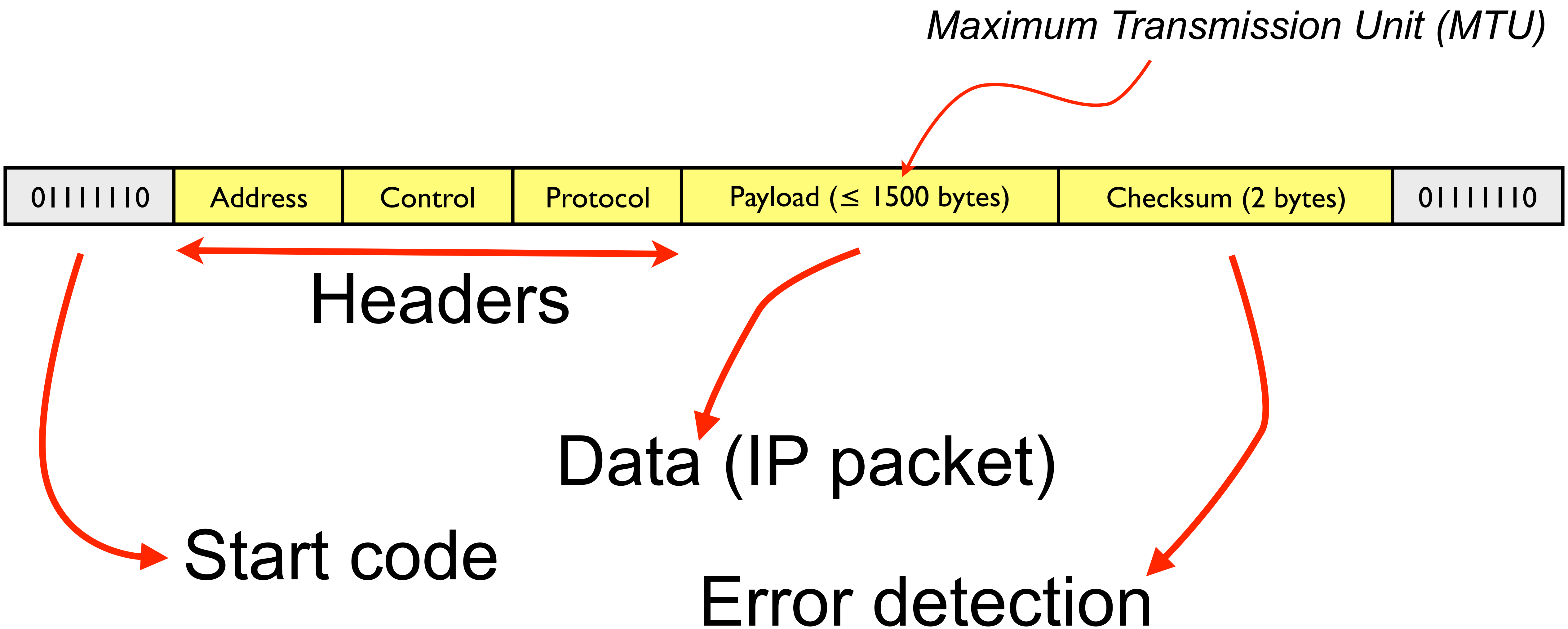
Framing and Synchronisation

- Physical layer provides unreliable raw bit stream
  - Bits might be corrupted
  - Timing can be disrupted
- Data link layer must correct these problems
  - Break the raw bit stream into *frames*
  - Transmit and repair individual frames
  - Limit scope of any transmission errors

Frame Structure



Example: PPP Frame



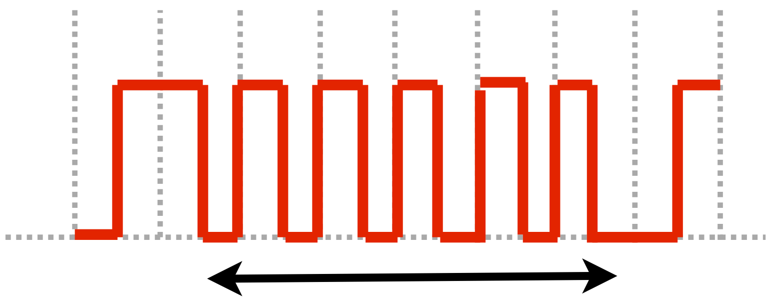
Synchronisation (1)

- How to detect the start of a message?
  - Leave gaps between frames
    - Problem – physical layer typically doesn't guarantee timing (clock skew, etc.)
  - Precede each frame with a length field
    - What if that length is corrupted? How to find next frame?
  - Add a special *start code* to beginning of frame
    - A unique bit pattern that *only* occurs at the start of each frame
    - Enables synchronisation after error – wait for next start code, begin reading frame headers

Synchronisation (2)

- What makes a good start code?
  - Must not appear in the frame headers, data, or error detecting code
  - Must allow timing recovery

0 1 1 1 1 1 1 0 →



Manchester Encoding

Start code should generate a regular pattern after physical layer coding

Receiver measures timing

Synchronisation (3)

- What if the start code appears in the data?
- Use *bit stuffing* to give a transparent channel
  - 11111→111110→11111
  - Can also use byte stuffing – double up the start code byte if it appears in the data

011011111111111111110010

Prepare for transmission

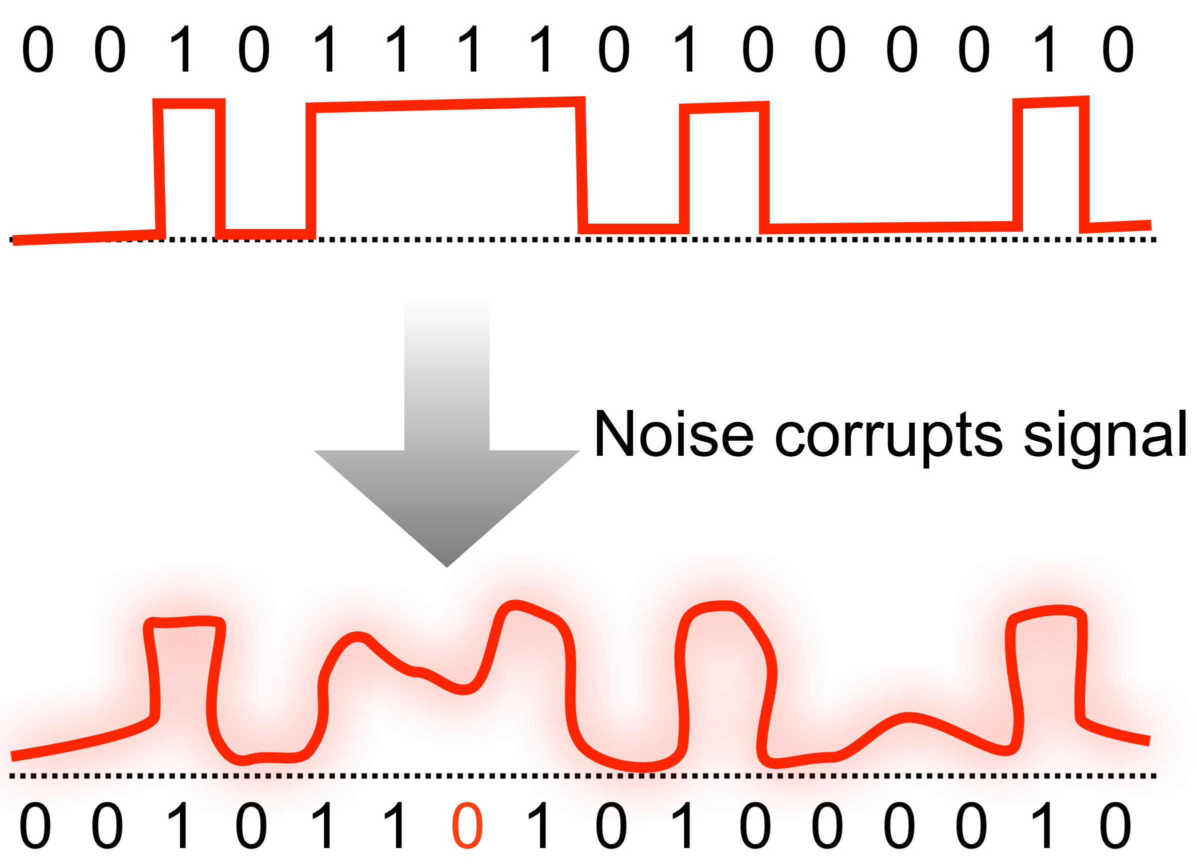
011011111011111011111010010

Stuffed bits

Destuff at receiver

011011111111111111110010

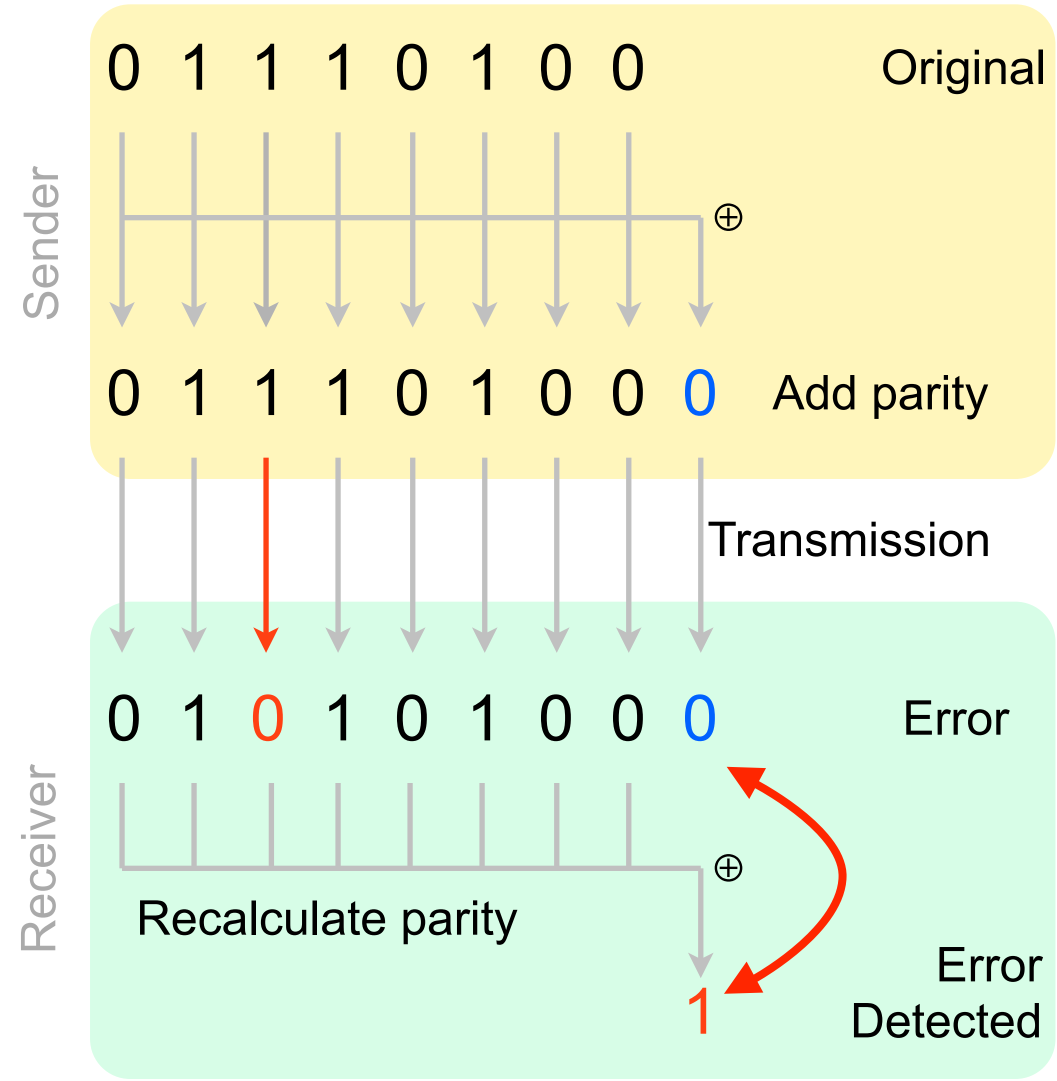
Error Detection



- Noise and interference at the physical layer can cause bit errors
  - Rare in wired links, common in wireless systems
- Add *error detecting code* to each packet

Parity Codes

- Simplest error detecting code
- Calculate *parity* of the data
  - How many 1 bits are in the data?
  - An odd number → parity 1
  - An even number → parity 0
  - Parity bit is the XOR (“⊕”) of data bits
- Transmit parity with the data, check at receiver
  - Detects all single bit errors



The Internet Checksum

```
#include <stdint.h>

// Internet checksum algorithm. Assumes
// data is padded to a 16-bit boundary.
uint16_t
internet_cksum(uint16_t *buf, int buflen)
{
    uint32_t sum = 0;

    while (buflen--) {
        sum += *(buf++);
        if (sum & 0xffff0000) {
            // Carry occurred, wrap around
            sum &= 0x0000ffff;
            sum++;
        }
    }
    return ~(sum & 0x0000ffff);
}
```

- Sum data values, send as a *checksum* in each frame
  - Internet protocol uses a 16 bit ones complement checksum
- Receiver recalculates, mismatch → bit error
- Better error detection than parity code
  - Detects many multiple bit errors

Other Error Detecting Codes

- Parity codes and checksums relatively weak
  - Simple to implement
  - Undetected errors reasonably likely
- More powerful error detecting codes exist
  - *Cyclic redundancy code* (CRC)
  - More complex → fewer undetected errors
  - (see recommended reading for details)

Error Correction

- How to correct bit errors?
  - Forward error correction (FEC)
    - Sender includes additional information in the initial transmission, allowing receiver to correct the error itself
  - Automatic repeat request (ARQ)
    - Receiver contacts sender to request a retransmission of the incorrect data

Forward Error Correction

- Extend error detecting codes to *correct* errors
  - Sender transmits error correcting code
    - Additional data within each frame
    - Additional frames
  - Allows receiver to correct (some) errors without contacting sender

FEC: Within a Frame

- Example: Hamming code
  - Send *n* data bits and *k* check bits every word
  - Check bits are sent as bits 1, 2, 4, 8, 16, …
  - Each check bit codes parity for some data bits
    - $b_1 = b_3 \oplus b_5 \oplus b_7 \oplus b_9 \oplus b_{11} \ldots$
    - $b_2 = b_3 \oplus b_6 \oplus b_7 \oplus b_{10} \oplus b_{11} \oplus b_{14} \oplus b_{15} \ldots$
    - $b_4 = b_5 \oplus b_6 \oplus b_7 \oplus b_{12} \oplus b_{13} \oplus b_{14} \oplus b_{15} \ldots$
    - i.e. starting at check bit *i*, check *i* bits, skip *i* bits, repeat

Richard Hamming

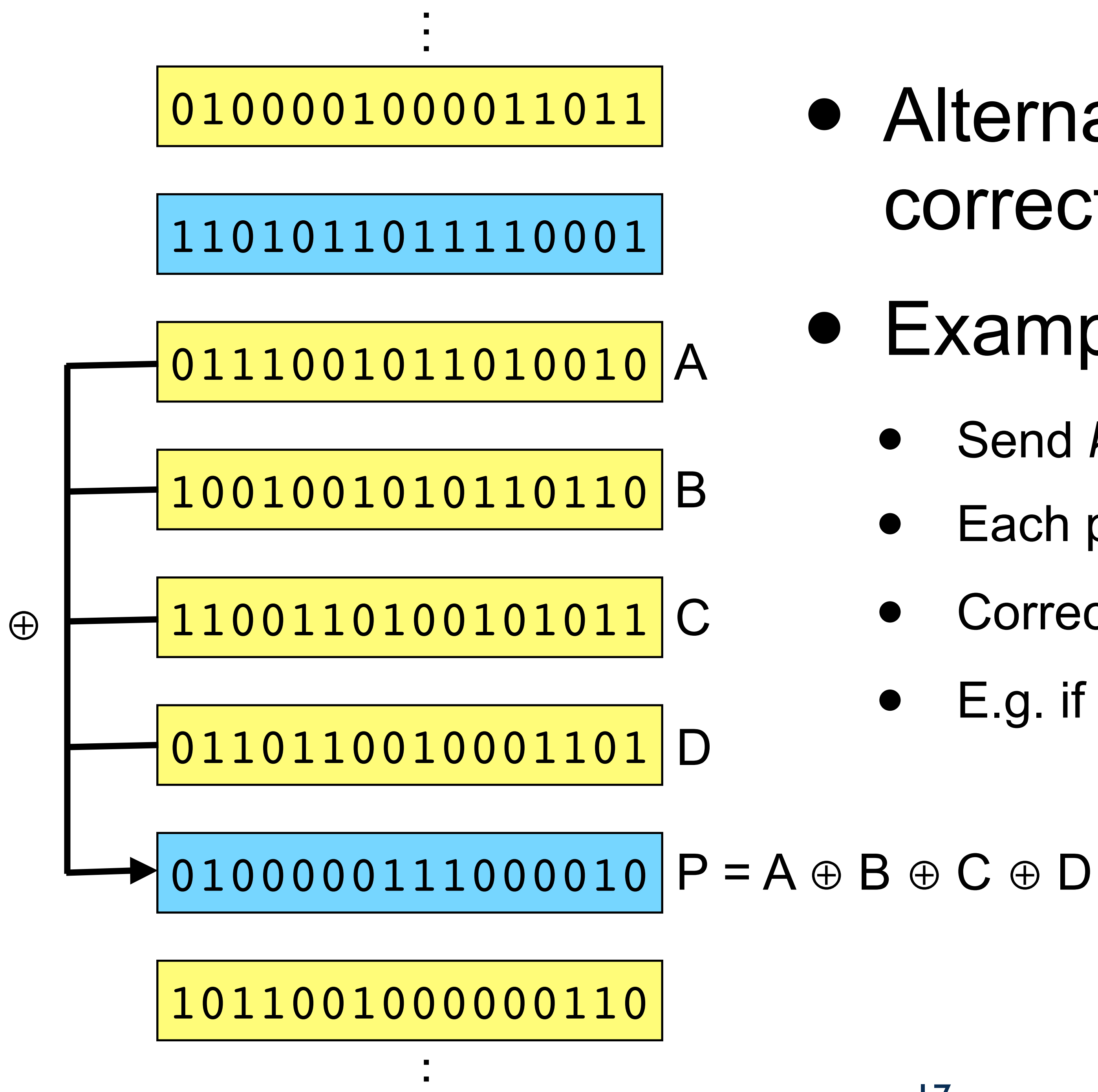
Character	ASCII	Hamming Code
H	1001000	00110010000
a	1100001	10111001001
m	1101101	11101010101
m	1101101	11101010101
i	1101001	01101011001
n	1101110	01101010110
g	1100111	11111001111
	0100000	10011000000
c	1100011	11111000011
o	1101111	00101011111
d	1100100	11111001100
e	1100101	00111000101

FEC: Within a Frame

- On reception:
  - Set *counter* = 0
  - Recalculate each check bit, *k*, in turn (*k* = 1, 2, 4, 8, …); if incorrect, *counter* += *k*
  - If (*counter* == *0*) {
    no errors
    } else {
    bit *counter* is incorrect
    }
- Allows correction of all single bit errors

Character	ASCII	Hamming Code
H	1001000	00110010000
a	1100001	10111001001
m	1101101	11101010101
m	1101101	11101010101
i	1101001	01101011001
n	1101110	01101010110
g	1100111	11111001111
	0100000	10011000000
c	1100011	11111000011
o	1101111	00101011111
d	1100100	11111001100
e	1100101	00111000101

FEC: Error Correcting Frames



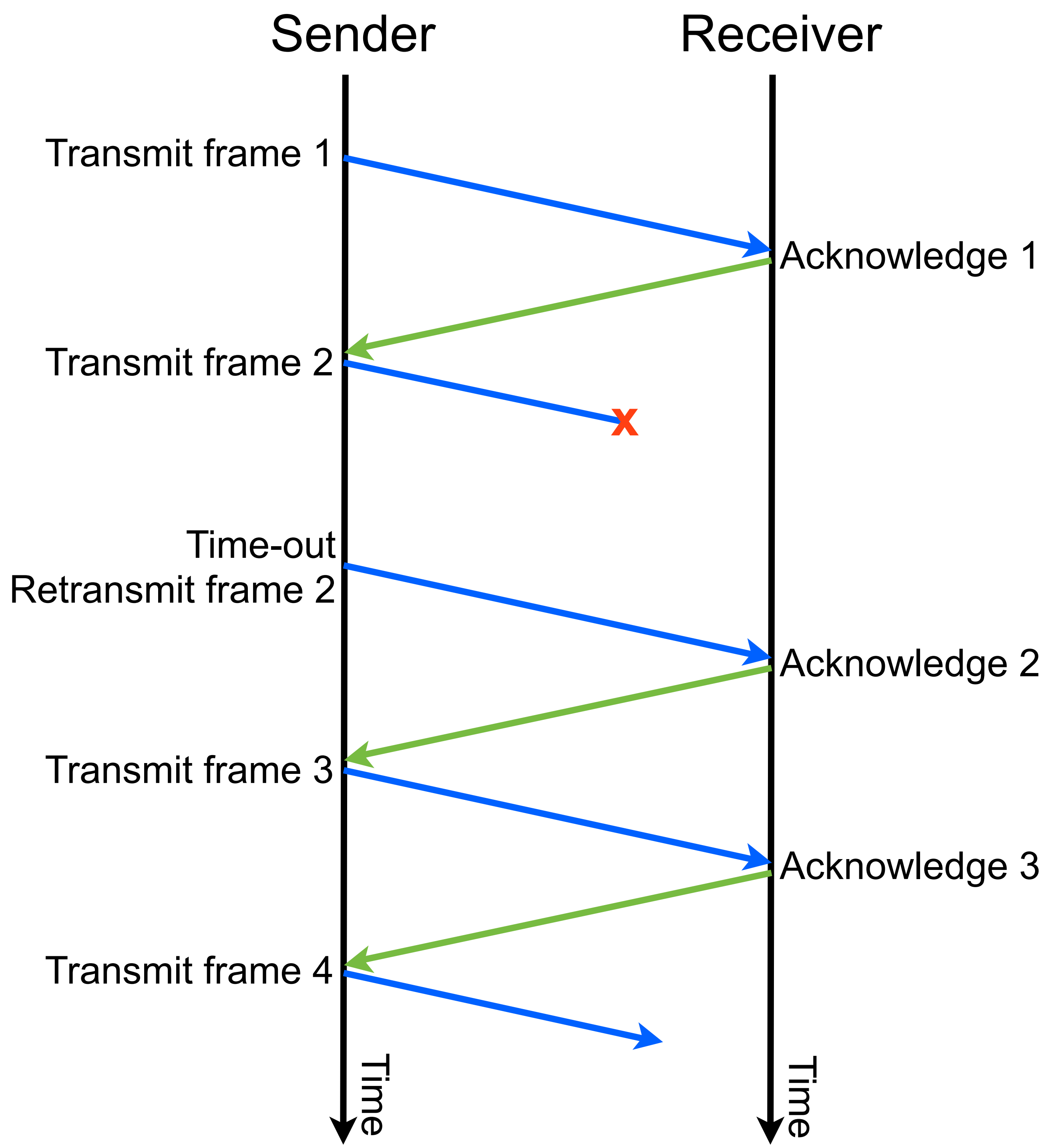
- Alternative: send extra error correcting frames
- Example: packet level parity
  - Send *k* parity packets every *n* data packets
  - Each parity packet is ⊕ of the data packets
  - Correct loss or error since ⊕ commutative
  - E.g. if B in error, repair B = A ⊕ C ⊕ D ⊕ P

Automatic Repeat Request

- Each frame includes a sequence number
- Receiver sends *acknowledgements* as it receives data frames
    - Can be sent as dedicated acknowledgement frames, or piggybacked onto returning data frames
    - Can be a positive acknowledgement (“I got frame *n*”) or a negative acknowledgement (“frame *n* is missing”)

Stop and Wait

- Simplest ARQ scheme:
  - Transmit a frame
  - Await positive acknowledgement from receiver
  - If no acknowledgement after some time out, retransmit frame
- Limitation:
  - One frame outstanding on link → limited performance on links with high bandwidth × delay product



Bandwidth × Delay Product

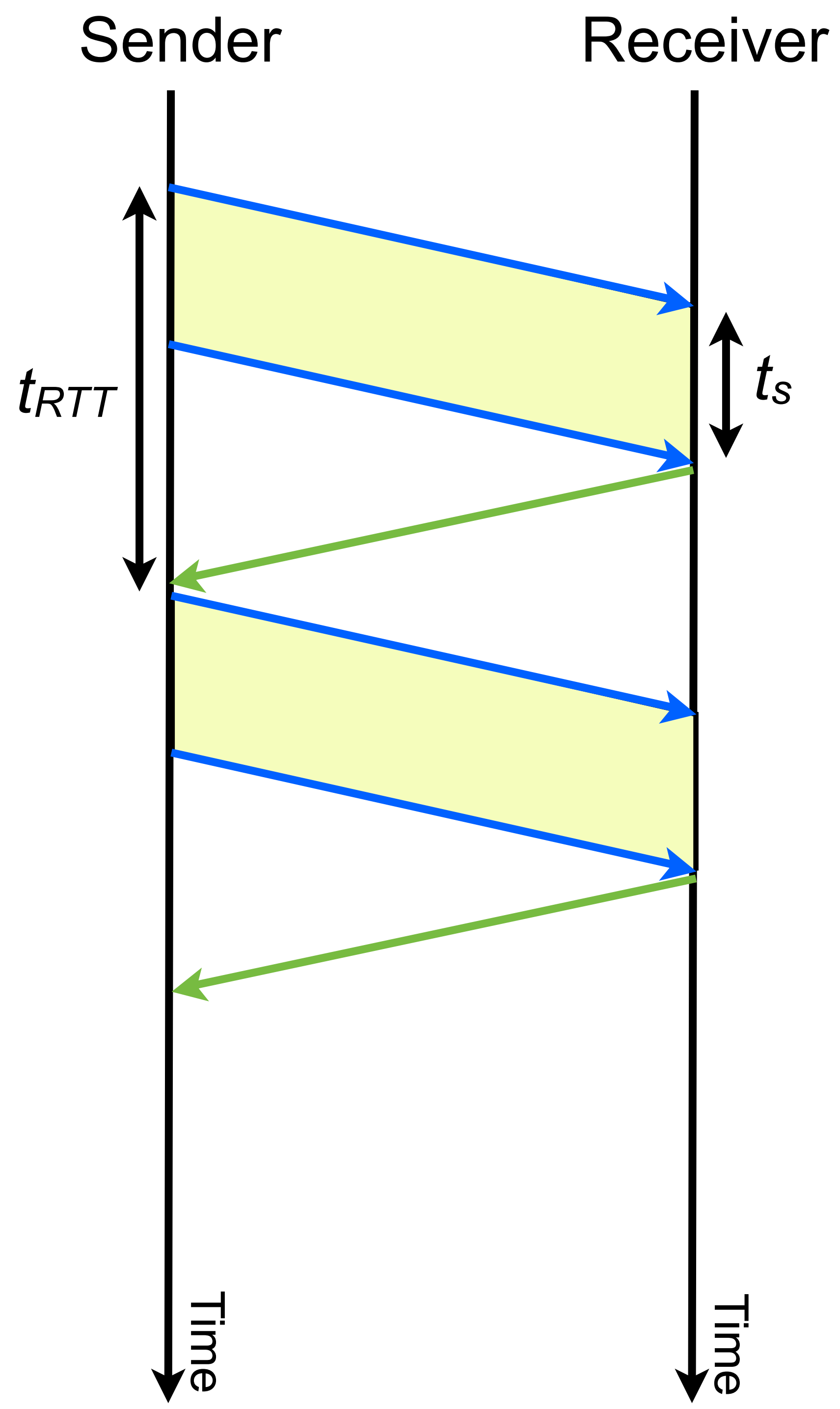
- Signal has limited speed:
  - ≈ 2.3×10^8 m/s in electrical cable, ≈ 2.0×10^8 m/s in optical fibre
- Determines propagation delay for the link
  - Baseline value – queuing will lead to higher delays
- Example link capacity:
  - Glasgow – London (~670km) → 3ms propagation delay

- Assume a 10 gigabit per second link speed
- 0.003 seconds x 10000000000 bits/second = 30000000 bits link capacity (~3.5 Mbytes of data in flight)

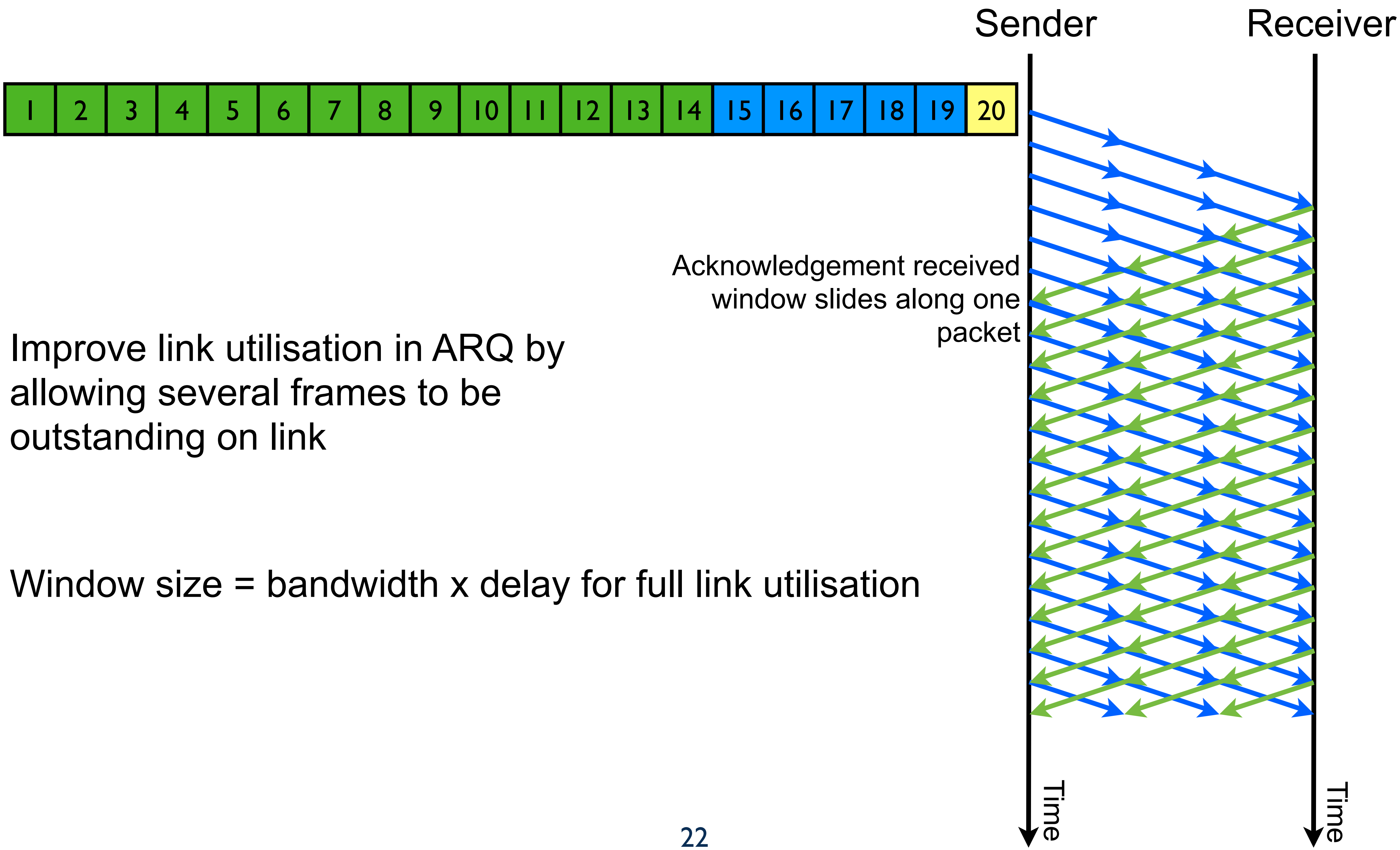
Bandwidth x delay = link capacity

Link Utilisation

- Assume it takes time, t_s, to serialise a frame onto link
  - t_s = (frame size) / (link bandwidth)
- Acknowledgement returns t_{RTT} seconds later
- Utilisation, $U = t_s / t_{RTT}$
  - Desire link fully utilised: $U \sim 1.0$
  - But $U \ll 1.0$ for stop-and-wait protocol



Sliding Window Protocol



Improve link utilisation in ARQ by allowing several frames to be outstanding on link

Window size = bandwidth x delay for full link utilisation

Sliding Window Protocol

- Stop-and-wait acceptable in LAN
  - Bandwidth delay product small, since RTT tiny
  - Reasonably efficient
- Variants on sliding window protocol required for wide area ARQ
  - How to choose window size? What is acknowledged?
  - Example: TCP congestion control

Questions?