Link Layer
Where we are in the Course

- Moving on up to the Link Layer!
Typical Implementation of Layers (2)
Scope of the Link Layer

• Concerns how to transfer messages over one or more connected links
  • Messages are **frames**, of limited size
  • Builds on the physical layer
In terms of layers ...
In terms of layers (2)
What are some challenges in the link layer?

What abstractions would we like to build?
Topics

1. Framing
   • Delimiting start/end of frames
2. Error detection and correction
   • Handling errors
3. Retransmissions
   • Handling loss
4. Multiple Access
   • 802.11, classic Ethernet
5. Switching
   • Modern Ethernet
Framing
Delimiting start/end of frames
The Physical layer gives us a stream of bits. How do we interpret it as a sequence of frames?
Simple ideas?
Framing Methods

• We’ll look at:
  • Byte count (motivation)
  • Byte stuffing
  • Bit stuffing

• In practice, the physical layer often helps to identify frame boundaries
  • E.g., Ethernet, 802.11
Byte Count

• First try:
  • Let’s start each frame with a length field!
  • It’s simple, and hopefully good enough ...
Byte Count (2)

How well do you think it works?
Byte Count (3)

• Difficult to re-synchronize after framing error
  • Want a way to scan for a start of frame
Byte Stuffing

• Better idea:
  • Have a special flag byte value for start/end of frame
  • Replace ("stuff") the flag with an escape code

Problem?
Byte Stuffing

• Better idea:
  • Have a special flag byte value for start/end of frame
  • Replace ("stuff") the flag with an escape code
  • Complication: have to escape the escape code too!
Byte Stuffing (2)

• Rules:
  • Replace each FLAG in data with ESC FLAG
  • Replace each ESC in data with ESC ESC
Byte Stuffing (3)

• Now any unescaped FLAG is the start/end of a frame

![Diagram showing byte stuffing examples]
Unstuffing

You see:

1. Solitary FLAG?
2. Solitary ESC?
3. ESC FLAG?
4. ESC ESC FLAG?
5. ESC ESC ESC FLAG?
6. ESC FLAG FLAG?
Unstuffing

You see:

1. Solitary FLAG? -> Start or end of packet
2. Solitary ESC? -> Bad packet!
3. ESC FLAG? -> remove ESC and pass FLAG through
4. ESC ESC FLAG? -> pass one ESC and then start of end of packet
5. ESC ESC ESC FLAG? -> pass ESC FLAG through
6. ESC FLAG FLAG? -> pass FLAG through then start of end of packet
Bit Stuffing

• Can stuff at the bit level too
  • Call a flag six consecutive 1s
  • On transmit, after five 1s in the data, insert a 0
  • On receive, a 0 after five 1s is deleted
Bit Stuffing (2)

- Example:

  Data bits: 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

  Transmitted bits with stuffing
Bit Stuffing (3)

• So how does it compare with byte stuffing?

Data bits: 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

Transmitted bits with stuffing:

Stuffed bits: 0 1 1 0 1 1 1 1 1 0 1 1 1 1 1 1 0 1 1 1 1 1 1 0 1 0 0 1 0
Link Example: PPP over SONET

• PPP is Point-to-Point Protocol
• Widely used for link framing
  • E.g., it is used to frame IP packets that are sent over SONET optical links
Link Example: PPP over SONET (2)

Think of SONET as a bit stream, and PPP as the framing that carries an IP packet over the link.

Protocol stacks

PPP frames may be split over SONET payloads
Link Example: PPP over SONET (3)

• Framing uses byte stuffing
  • FLAG is 0x7E and ESC is 0x7D
Link Layer: Error detection and correction
Topic

• Some bits will be received in error due to noise. What can we do?
  Detect errors with codes
  Correct errors with codes
  Retransmit lost frames

Later

• Reliability is a concern that cuts across the layers
Problem – Noise may flip received bits

<table>
<thead>
<tr>
<th>Signal</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slightly Noisy</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Noisy</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Very Noisy</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
• Ideas?
Approach – Add Redundancy

• Error detection codes
  • Add check bits to the message bits to let some errors be detected

• Error correction codes
  • Add more check bits to let some errors be corrected

• Key issue is now to structure the code to detect many errors with few check bits and modest computation
• Ideas?
Motivating Example

• A simple code to handle errors:
  • Send two copies! Error if different.

• How good is this code?
  • How many errors can it detect/correct?
  • How many errors will make it fail?
Motivating Example (2)

• We want to handle more errors with less overhead
  • Will look at better codes; they are applied mathematics
  • But, they can’t handle all errors
  • And they focus on accidental errors (will look at secure hashes later)
Using Error Codes

• Codeword consists of D data plus R check bits (=systematic block code)

<table>
<thead>
<tr>
<th>Data bits</th>
<th>Check bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>R = fn(D)</td>
</tr>
</tbody>
</table>

• Sender:
  • Compute R check bits based on the D data bits; send the codeword of D+R bits
Using Error Codes (2)

• Receiver:
  • Receive D+R bits with unknown errors
  • Recompute R check bits based on the D data bits; error if R doesn’t match R’
Intuition for Error Codes

• For D data bits, R check bits:

Randomly chosen codeword is unlikely to be correct; overhead is low

All codewords

Correct codewords
R.W. Hamming (1915-1998)

• Much early work on codes:
  • “Error Detecting and Error Correcting Codes”, BSTJ, 1950
  • “If the computer can tell when an error has occurred, surely there is a way of telling where the error is so the computer can correct the error itself” - Hamming

Source: IEEE GHN, © 2009 IEEE
Hamming Distance

• Distance is the number of bit flips needed to change $D_1$ to $D_2$

• Hamming distance of a coding is the minimum error distance between any pair of codewords (bit-strings) that cannot be detected
Hamming Distance (2)

• Error detection:
  • For a coding of distance $d+1$, up to $d$ errors will always be detected

• Error correction:
  • For a coding of distance $2d+1$, up to $d$ errors can always be corrected by mapping to the closest valid codeword
Simple Error Detection – Parity Bit

• Take D data bits, add 1 check bit that is the sum of the D bits
  • Sum is modulo 2 or XOR
Parity Bit (2)

• How well does parity work?
  • What is the distance of the code?
  • How many errors will it detect/correct?

• What about larger errors?
Checksums

• Idea: sum up data in N-bit words
  • Widely used in, e.g., TCP/IP/UDP

| 1500 bytes | 16 bits |

• Stronger protection than parity
Internet Checksum

• Sum is defined in 1s complement arithmetic (must add back carries)
  • And it’s the negative sum
• “The checksum field is the 16 bit one's complement of the one's complement sum of all 16 bit words ...” – RFC 791
Internet Checksum (2)

Sending:
1. Arrange data in 16-bit words
2. Put zero in checksum position, add
3. Add any carryover back to get 16 bits
4. Negate (complement) to get sum

\[
\begin{array}{c}
\text{0001} \\
\text{f204} \\
\text{f4f5} \\
\text{f6f7} \\
\end{array}
\]
Internet Checksum (3)

Sending:
1. Arrange data in 16-bit words
2. Put zero in checksum position, add
3. Add any carryover back to get 16 bits
4. Negate (complement) to get sum
Internet Checksum (4)

Receiving:
1. Arrange data in 16-bit words
2. Checksum will be non-zero, add
3. Add any carryover back to get 16 bits
4. Negate the result and check it is 0

\[
\begin{align*}
0001 & \quad f2\text{04} \\
\text{f4f5} & \quad \text{f6f7} \\
+ \quad 22\text{0c} & \quad \text{- - - - - -}
\end{align*}
\]
Internet Checksum (5)

Receiving:
1. Arrange data in 16-bit words
2. Checksum will be non-zero, add
3. Add any carryover back to get 16 bits
4. Negate the result and check it is 0

\[
\begin{array}{c}
0001 \\
f204 \\
f4f5 \\
f6f7 \\
+ \quad 220c \\
- \cdots \cdots \\
2fffd \\
\quad ffffd \\
\quad + \quad 2 \\
- \cdots \cdots \\
\quad ffff \\
\quad \downarrow \quad 0000
\end{array}
\]
Internet Checksum (6)

• How well does the checksum work?
  • What is the distance of the code?
  • How many errors will it detect/correct?

• What about larger errors?
Cyclic Redundancy Check (CRC)

• Even stronger protection
  • Given $n$ data bits, generate $k$ check bits such that the $n+k$ bits are evenly divisible by a generator $C$

• Example with numbers:
  • $n = 302$, $k = \text{one digit}$, $C = 3$
CRCs (2)

• The catch:
  • It’s based on mathematics of finite fields, in which “numbers” represent polynomials
  • e.g, $10011010$ is $x^7 + x^4 + x^3 + x^1$

• What this means:
  • We work with binary values and operate using modulo 2 arithmetic
CRCs (3)

• Send Procedure:
  1. Extend the n data bits with k zeros
  2. Divide by the generator value C
  3. Keep remainder, ignore quotient
  4. Adjust k check bits by remainder

• Receive Procedure:
  1. Divide and check for zero remainder
CRCs (4)

Data bits: 1 0 0 1 1 | 1 1 0 1 0 1 1 1 1 1 1
1101011111

Check bits: C(x) = x^4 + x^1 + 1
C = 10011
k = 4
CRCs (5)
CRCs (6)

• Protection depend on generator
  • Standard CRC-32 is 10000010 01100000 10001110 110110111

• Properties:
  • HD=4, detects up to triple bit errors
  • Also odd number of errors
  • And bursts of up to k bits in error
  • Not vulnerable to systematic errors like checksums
Why Error Correction is Hard

• If we had reliable check bits we could use them to narrow down the position of the error
  • Then correction would be easy
• But error could be in the check bits as well as the data bits!
  • Data might even be correct
Intuition for Error Correcting Code

• Suppose we construct a code with a Hamming distance of at least 3
  • Need ≥3 bit errors to change one valid codeword into another
  • Single bit errors will be closest to a unique valid codeword

• If we assume errors are only 1 bit, we can correct them by mapping an error to the closest valid codeword
  • Works for d errors if HD ≥ 2d + 1
Intuition (2)

• Visualization of code:
Intuition (3)

- Visualization of code:

  - Single bit error from A
  - Three bit errors to get to B
  - Valid codeword
  - Error codeword
Hamming Code

• Gives a method for constructing a code with a distance of 3
  • Uses $n = 2^k - k - 1$, e.g., $n=4$, $k=3$
  • Put check bits in positions $p$ that are powers of 2, starting with position 1
  • Check bit in position $p$ is parity of positions with a $p$ term in their values

• Plus an easy way to correct [soon]
Hamming Code (2)

• Example: data=0101, 3 check bits
  • 7 bit code, check bit positions 1, 2, 4
  • Check 1 covers positions 1, 3, 5, 7
  • Check 2 covers positions 2, 3, 6, 7
  • Check 4 covers positions 4, 5, 6, 7
Hamming Code (3)

• Example: data=0101, 3 check bits
  • 7 bit code, check bit positions 1, 2, 4
  • Check 1 covers positions 1, 3, 5, 7
  • Check 2 covers positions 2, 3, 6, 7
  • Check 4 covers positions 4, 5, 6, 7

```
0 1 0 0 1 0 1
```

\[
p_1 = 0+1+1 = 0, \quad p_2 = 0+0+1 = 1, \quad p_4 = 1+0+1 = 0
\]
Hamming Code (4)

• To decode:
  • Recompute check bits (with parity sum including the check bit)
  • Arrange as a binary number
  • Value (syndrome) tells error position
  • Value of zero means no error
  • Otherwise, flip bit to correct
Hamming Code (5)

• Example, continued

\[
\begin{array}{cccccccc}
\text{0} & \text{1} & \text{0} & \text{0} & \text{1} & \text{0} & \text{1} \\
1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\end{array}
\]

\[p_1=\]
\[p_2=\]
\[p_4=\]

Syndrome =
Data =
Hamming Code (6)

• Example, continued

\[
\begin{array}{ccccccc}
0 & 1 & 0 & 0 & 1 & 0 & 1 \\
1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\end{array}
\]

\[
p_1 = 0+0+1+1 = 0, \quad p_2 = 1+0+0+1 = 0, \\
p_4 = 0+1+0+1 = 0
\]

Syndrome = 000, no error
Data = 0 1 0 1
Hamming Code (7)

• Example, continued

\[\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 1 & 1 & 1 \\
\end{array}\]

\[\begin{array}{cccccccc}
1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\end{array}\]

\[p_1 = \quad p_2 = \]

\[p_4 = \]

Syndrome =

Data =
Hamming Code (8)

• Example, continued

\[
\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 1 & 1 & 1 \\
1 & 2 & 3 & 4 & 5 & 6 & 7
\end{array}
\]

\[p_1 = 0+0+1+1 = 0, \quad p_2 = 1+0+1+1 = 1,\]

\[p_4 = 0+1+1+1 = 1\]

Syndrome = 1 1 0, flip position 6
Data = 0 1 0 1 (correct after flip!)
Hamming Code (3)

• Example: bad message 0100111
  • 7 bit code, check bit positions 1, 2, 4
  • Check 1 covers positions 1, 3, 5, 7
  • Check 2 covers positions 2, 3, 6, 7
  • Check 4 covers positions 4, 5, 6, 7

\[
\begin{array}{cccccccc}
0 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\
1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\end{array}
\]

\[p_1 = 0+0+1+1 = 0, \quad p_2 = 1+0+1+1 = 1, \quad p_4 = 0+1+1+1 = 1\]
Hamming Code (3)

• Example: bad message 0100111
  • 7 bit code, check bit positions 1, 2, 4
  • Check 1 covers positions 1, 3, 5, 7
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\[
\begin{align*}
\text{0} & \quad \text{1} & \quad \text{0} & \quad \text{0} & \quad \text{1} & \quad \text{1} & \quad \text{1} \\
1 & 2 & 3 & 4 & 5 & 6 & 7
\end{align*}
\]

\[p_1 = 0 + 0 + 1 + 1 = 0, \quad p_2 = 1 + 0 + \textcolor{red}{1} + 1 = 1, \quad p_4 = 0 + 1 + 1 + 1 = 1\]
Other Error Correction Codes

- Real codes are more involved than Hamming
- E.g., Convolutional codes (§3.2.3)
  - Take a stream of data and output a mix of the input bits
  - Makes each output bit less fragile
  - Decode using Viterbi algorithm (which can use bit confidence values)
Other Codes (2) – Turbo Codes

• Turbo Codes
  • Evolution of convolutional codes
  • Sends multiple sets of parity bits with payload
  • Decodes sets together (e.g. Sudoku)
  • Used in 3G and 4G cellular technologies

• Invented and patented by Claude Berrou
  • Professor at École Nationale Supérieure des Télécommunications de Bretagne
Other Codes (3) – LDPC

• Low Density Parity Check (§3.2.3)
  • LDPC based on sparse matrices
  • Decoded iteratively using a belief propagation algorithm

• Invented by Robert Gallager in 1963 as part of his PhD thesis
  • Promptly forgotten until 1996 ...
Detection vs. Correction

• Which is better will depend on the pattern of errors. For example:
  • 1000 bit messages with a bit error rate (BER) of 1 in 10000

• Which has less overhead?
Detection vs. Correction

• Which is better will depend on the pattern of errors. For example:
  • 1000 bit messages with a bit error rate (BER) of 1 in 10000

• Which has less overhead?
  • It still depends! We need to know more about the errors
Detection vs. Correction (2)

Assume bit errors are random
- Messages have 0 or maybe 1 error (1/10 of the time)

Error correction:
- Need ~10 check bits per message
- Overhead:

Error detection:
- Need ~1 check bits per message plus 1000 bit retransmission
- Overhead:
Detection vs. Correction (3)

Assume errors come in bursts of 100
  • Only 1 or 2 messages in 1000 have significant (multi-bit) errors

Error correction:
  • Need $\gg 100$ check bits per message
  • Overhead:

Error detection:
  • Need 32 check bits per message plus 1000 bit resend $2/1000$ of the time
  • Overhead:
Detection vs. Correction (4)

• Error correction:
  • Needed when errors are expected
  • Or when no time for retransmission

• Error detection:
  • More efficient when errors are not expected
  • And when errors are large when they do occur
Error Correction in Practice

• Heavily used in physical layer
  • LDPC is the future, used for demanding links like 802.11, DVB, WiMAX, power-line, ...
  • Convolutional codes widely used in practice

• Error detection (w/ retransmission) is used in the link layer and above for residual errors

• Correction also used in the application layer
  • Called Forward Error Correction (FEC)
  • Normally with an erasure error model
  • E.g., Reed-Solomon (CDs, DVDs, etc.)