SEMESTER II EXAMINATIONS - 2013-2014

EEEN 20060 - Communication Systems

Outline Solutions

Question 1

Answer any **four** parts of this question. All parts carry equal marks.

a) Figure 1 shows a segment of a Manchester coded signal. The tick marks on the time axis are at 1 μs intervals. State the bit rate and identify the bits shown. Explain briefly how you arrive at your answers.

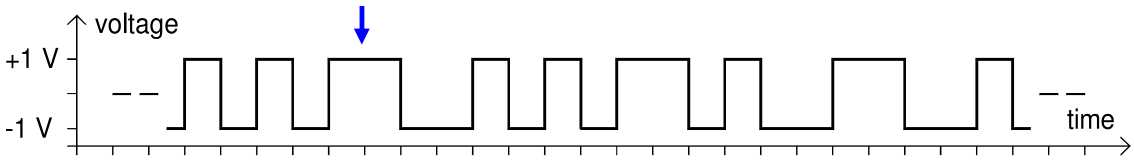

Figure 1: Received Signal

In Manchester coding, each bit has a transition at the centre, and may also have a transition at the edge. In this signal, each bit lasts for 2 μs, so the bit rate is 500 kbit/s.

To identify the bits, it is necessary to find the start of a bit interval. Reading from the left, the first 5 transitions could be at the edge or the centre of a bit, but the absence of a transition at the point marked by an arrow means that this must be the edge of a bit. Working back from this, the first transition shown is at the centre of a bit, and as it is an upward transition, the bit value is 1.

The bits are 1 1 1 0 1 1 1 0 0 1 0 1 .

b) A link-layer protocol uses short frames with a cyclic redundancy check on the frame content for error detection. The divisor is 1001. Calculate the check bits that should be appended to the frame below, where the leftmost bit is transmitted first. Explain briefly how the received frame will be checked for errors.

1 0 0 0 1 1 0 1 1 0

A 4-bit divisor will give a 3-bit remainder, so first add three 0 bits to the end of the sequence of bits given. Then divide by 1001, modulo 2. This gives remainder 001. Replace the three 0 bits with this remainder, so the bits transmitted are 1 0 0 0 1 1 0 1 1 0 0 0 1 .

The receiver divides the received bits by 1001 in the same way, and should get remainder 000 if there have been no errors.

c) A physical layer protocol delivers 1024 kbit/s. It uses an advanced modulation scheme, which tends to produce errors in bursts of up to 20 bit errors. The occurrence of these bursts can be modelled as a Poisson random process, with an average rate of 6.3 burst/s. The link layer protocol transmits frames containing 3000 data bits, with another 72 bits in the header and trailer. What is the probability of a frame being received without errors? What type of error detecting code would be needed?

For a Poisson random process, with average rate of events λ, the probability of no events in time interval T is $P_0(T) = e^{-\lambda T}$. For a frame to be received without errors, there must be no error burst in the time taken to transmit the frame, $T_F = \frac{3072 \text{ bit}}{1024 \times 10^3 \text{ bit/s}} = 3$ ms. Probability of no error burst in this time is 0.9813.

The error detecting code must be able to handle burst of up to 20 bit errors. For example, a parity check should use interleaving, to spread the error burst over many separate checked groups. A checksum would need to add groups of at least 11 bits, to ensure that an error burst could not affect all the bits of two groups. A CRC would need a long divisor – more than 20 bits.

d) In the context of a packet-switched network, outline the advantages and disadvantages of a connection-based service. Also explain how such a service could be provided by the network.

Advantages: Connections allow a reliable service to be provided. It is possible to guarantee the arrival of packets, and also to guarantee arrival in the correct order. If the connection is implemented by having all the packets follow the same path, then the network only has to make routing decisions on the connection request packet, reducing its workload, and it is possible to reserve resources along that path, to reduce delay variation.

Disadvantages: There is a delay in establishing the connection, which can outweigh the savings if the number of packets sent on the connection is small. The network-layer protocol is much more complicated, and has more work to do. If all the packets follow the same path, there is no flexibility to change the route during a connection, to adapt to changing traffic in the network.

How to provide: Can ensure delivery by checking packet sequence numbers at the destination. Can ensure delivery in sequence by re-ordering packets at the destination, using the sequence number, or by forcing all packets to follow the same route. In the second case, the route taken by the connection request packet is recorded at each node, and virtual circuit numbers are assigned to the connection on each link. All the following packets use the same virtual circuit numbers, and are sent on the same route.

e) Figure 2 shows a small network that uses link-state routing. The number beside each link indicates the cost of using that link. Explain briefly how this operates. Show an example of the routing message that might be sent by node G. Consider a situation where the network has been operating for some time, and the link between node A and node D fails. How would node G find out about this? What effect would this have on the routing decisions at node G? Also consider the effect of adding a new link, with cost 2, between node B and node J. What effect would this have on the routing decisions at node G?

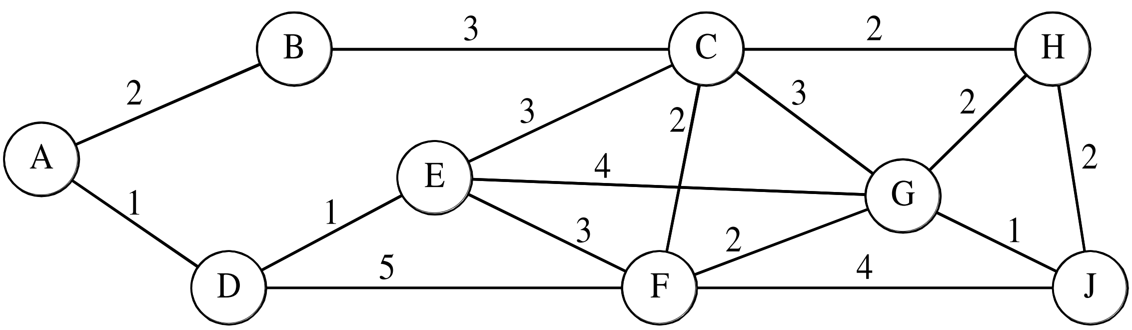

Figure 2: Network Diagram

Operation: Each node broadcasts details of its own links at intervals. The broadcasts use flooding (copy and send on all links), but with a sequence number to distinguish new from old and allow duplicates to be discarded; and a hop counter so older packets can be discarded and not circulate forever in the network. Each node builds its own map of the network, based on the information received from the other nodes.

Message from G: node G; sequence 27; hop 0; C 3; E 4; F 2; H 2; J 1.

A-D fails: Both A and D realise this, and send new broadcasts to inform other nodes. G will receive these broadcasts. G will only have been using this link for traffic to node A (route

G-E-D-A, with cost 6). It will now update its routing table, and send traffic for A to node C, expecting C to send the traffic to B, which should send it on to A. Cost for the new route is 8.

New link: The new link will provide better routes to nodes A and B, so node G will update its routing table accordingly, and start sending traffic for A and B via node J.

Question 2

Design a link-layer protocol to provide reliable continuous transmission of images on a point-to-point link from a satellite observatory (telescope) in geostationary orbit to a laboratory in Dublin, at a distance from the satellite of 38,700 km. You may assume that the speed of light is 3×10^{8} m/s.

The physical layer provides a full-duplex path at 8 Mbit/s, using a separate frequency for uplink and downlink. Each bit has probability of error 5×10^{-6}.

a) Give details of your design. In particular, specify:
- how the start and end of a frame will be recognised reliably;
- header and trailer contents, including the number of bits allocated to each item;
- what responses the receiver will send;
- what the sender will do while waiting for a response;
- what the sender will do if it receives a negative response;
- what the sender will do if it receives no response.

Also estimate the size of the sending and receiving windows (if any), assuming a frame size of about 3000 bits. Give reasons for your design decisions. (50%)

The propagation delay on the link is 129 ms. At the bit rate specified, this corresponds to 1023 kbit, or 344 frames of 3000 bits. So a stop and wait protocol would be very inefficient. The full-duplex link makes it possible to use a sliding window protocol, and the long delay makes it worthwhile to use selective reject.

Example design details (other proposals are also valid):

Start and end are marked using flags. Bit stuffing is used to prevent a flag from occurring during transmission of the rest of the frame.

Header needs start flag of 8 bits, sequence number of 11 bits (see below), perhaps a few bits to identify frame type. Trailer needs error-detecting code – say 16-bit CRC – and end flag. Total overhead could be 48 bits, plus any stuff bits added.

Receiver will respond with an acknowledgement frame, carrying the sequence number of the last good data block received.

Sender will continue sending frames with new data blocks.

If it receives a negative response, sender will finish the frame in progress, then resend the data block that was received with errors, and resume where it left off.

The sender will wait for a response (while sending more frames) up to some time limit, which should be set slightly higher than the round-trip delay – say 270 ms. If there is no acknowledgement for a particular frame at that point, it should re-send the frame.

Consider block N being sent in a frame. Received after 1 propagation delay, but with errors. Response sent with sequence number of previous good block, received after another propagation delay. Block send again, received after a third propagation delay, with no errors. Response sent with sequence number N, received after four propagation delays. Finally, the data block can be discarded at the sender, and the sequence number made available for re-use.

So to allow continuous transmission with an occasional frame in error, the sending window size must be more than the number of frames sent during 4 propagation delays, or 516 ms. This is

1376 frames of 3000 bits. So use an 11-bit sequence number and make the sending window size 2000.

The receiving window need only be half this size, or 1000 frames.

b) Calculate the optimum number of data bits in a frame (to maximise throughput). (If you cannot do this, assume a sensible number, so that you can continue.) Calculate the throughput that your protocol could deliver using data blocks of the optimum size. Show clearly how you arrive at your answers, and explain any additional assumptions that you make. (50%)

Throughput for selective reject is given by $= \frac{DRP_S}{D+H}$, where D is the number of data bits in a frame, H is the number of overhead bits, R is the bit rate and P_S is the probability of successful transmission.

Success requires no error in the frame or in the acknowledgement, of A bits. With probability of bit error p, this is $P_S = (1-p)^{(D+H+A)}$.

Assume header and trailer contain 48 bits, as in part (a). Stuff bits will be added, on average one for every 32 bits (excluding the two flags). Thus $H = 49 + \frac{D}{32}$. Assume $A = 49$ bits also.

Thus $U = \frac{DRs^{(kD+98)}}{kD+49}$, where $s = 1-p$ and $k = \frac{33}{32}$.

Differentiating to find the optimum:

$$\frac{dU}{dD} = \frac{(kD+49)\left[Rs^{(kD+98)} + kDRs^{(kD+98)}\ln(s)\right] - kDRs^{(kD+98)}}{(kD+49)^2} = 0$$

$$\Rightarrow k^2D^2\ln(s) + 49kD\ln(s) + 49 = 0$$

$$\Rightarrow D_{optimum} = \frac{1}{2k}\left[\sqrt{49^2 - \frac{4(49)}{\ln(s)}} - 49\right] \approx \frac{1}{2k}\left[\sqrt{49^2 + \frac{4(49)}{p}} - 49\right] \approx 3012 \text{ bits}$$

since $\ln(s) = \ln(1-p) \approx -p$ for small p.

Using this value of D gives throughput 7.516 Mbit/s.

Question 3

Binary signals are transmitted on an optical fibre by turning the light source on or off for the entire duration of each bit interval. When the light source is on, it outputs its maximum power of 50 mW. At the optical frequency used, the fibre has attenuation 0.4 dB/km. At the receiver, a photo-diode converts the light to an electrical signal, giving an output voltage proportional to the power of the incoming light (500 V/W), plus noise with Gaussian probability density function. At a distance of 100 km, the probability of error in the receiver is barely acceptable.

a) Sketch the eye diagram that you would expect to see at the photo-diode output at a distance of 100 km. Give two reasons why this is not just a scaled version of what might be seen at the transmitter. Calculate the voltages that you would expect at the photo-diode output (in the absence of noise) when a 1 or a 0 is transmitted continuously, and mark these on the eye diagram. Explain how the receiver should make decisions. (40%)

Optical fibre 100 km long has attenuation 40 dB, so receive power (when light is on) will be 5 µW. Photodiode will convert this to a voltage of 2.5 mV.

Eye diagram should show signals changing between the two expected values of 0 V and 2.5 mV, with slow transitions and a lot of random variation, due to noise. As probability of error is barely acceptable, eye opening should be small.

Differs from transmitted signal due to distortion in channel – signal shape changed from rectangular pulses, also depends on signals transmitted before and after the one in question.

Differs from transmitted signal due to random noise, which was not present at the transmitter.

Receiver should make decisions by setting a threshold mid-way between the expected values, at 1.25 mV. Then sample at the centre of the eye opening (point of maximum opening), and compare the sample with the threshold.

b) Propose a method of transmitting data over a distance of thousands of km, using the same technology as in part a. Give details of your proposal. (20%)

Use regenerators. Receive the signal at a distance where the probability of error is very low, make a decision, and transmit a new signal. Repeat until reach destination. Distance could be 80 km, for example. Attenuation is then 32 dB, so S/N at receiver should be 8 dB higher than at 100 km. That should reduce the probability of error by several orders of magnitude (see example graph in lecture notes).

c) You want to double the bit rate of the system in part a, without increasing the bandwidth, by using a larger set of signals. Explain how this could be done. Propose suitable values for the output power of the light source, keeping to the maximum of 50 mW. Calculate the distance at which the probability of error would be the same as that achieved in the original design (at 100 km, as in part a). (40%)

To double the bit rate, each signal must carry 2 bits. So need a set of 4 signals. As the only variable here is light output power, need to use 4 different power levels, between 0 and the maximum of 50 mW.

Equally spaced values will give the lowest overall probability of error at the receiver, so choose 0, 16.7, 33.3 and 50 mW.

The power difference between adjacent signals is reduced by a factor of 3, compared to the original binary system. The receiver will now need 3 thresholds, and at the same distance, the voltage difference between the expected value and the threshold would be reduced by a factor of 3. To restore the original probability of the added noise pushing the signal over the threshold, the signal voltages at the photodiode output need to be increased by a factor of 3, which means the received optical power needs to be increased by a factor of 3, or 4.77 dB. So need to reduce the distance by 12 km, to 88 km.

(Note that this is an over-simplification. The two inner signals now have twice the probability of error of the outer signals – for those signals, the noise could push the voltage over either one of two equi-distant thresholds. That would increase the probability of choosing the wrong signal. However, if the bits are mapped to signals using a Gray code, most decision errors will only cause one bit error, so the probability of bit error is approximately half the probability of decision error…)

Question 4

Thirty devices are connected in parallel on one cable, so that all devices receive all transmissions. The physical-layer bit rate is 200 kbit/s and the total cable length is 1 km. The link-layer protocol uses frames that vary in length from 100 to 4000 bit (including header and trailer), with average payload 2800 bit. On average, all devices produce approximately equal traffic. Each device typically communicates with many other devices in the network.

a) The system currently uses slotted Aloha as the medium access control protocol. Explain how this would work, and propose a suitable duration for the time slot. Calculate the maximum throughput that this system could deliver (in bit/s), stating clearly any assumptions that you make. (50%)

The channel is divided into time slots, long enough to hold one frame. A device wanting to transmit must wait for the start of a time slot, then transmit. As all devices receive all transmissions, the device should receive its own transmission – if it does not, it knows that a collision has occurred. (Alternatively, it could recognise a collision by the lack of an acknowledgement.) It must then wait for some random time interval before attempting to re-transmit.

The maximum frame of 4000 bit will take 20 ms to transmit. This would be a suitable time slot length: T_S = 20 ms.

Assume blocks of data arrive for transmission, across all the devices, as a Poisson random process, with average rate λ. Assume that the backoff algorithm gives a total transmission attempt rate (new and re-transmissions) that can also be modelled as a Poisson random process, with average attempt rate λ'. This will be greater than the average rate of arrivals – the ratio is the probability of successful transmission, so $\lambda = \lambda' P_S$.

The probability of successful transmission is the probability of no device becoming ready to transmit in time T_S (the previous time slot), so $P_S = e^{-\lambda' T_S}$.

Combining the two equations, $\lambda = \lambda' e^{-\lambda' T_S}$. Differentiate this to find the maximum:

$$\frac{d\lambda}{d\lambda'} = e^{-\lambda' T_S} + \lambda' e^{-\lambda' T_S}(-T_S) = 0 \;\Rightarrow\; 1 - \lambda' T_S = 0 \;\Rightarrow\; \lambda' = \frac{1}{T_S}$$

This gives $\lambda_{max} = \frac{1}{T_S} e^{-1}$ = 18.39 data blocks per second. At an average of 2800 bit per block, the maximum throughput is 51.5 kbit/s.

b) Describe two alternative medium-access control protocols that could provide a higher throughput in this system, including at least one without contention. In each case, explain why you think the protocol that you are describing would allow a higher throughput, and whether a master device would be required. Choose one of the two protocols that you have described and estimate the throughput that it could provide under ideal conditions. State clearly any assumptions that you make. (50%)

Example: CSMA/CD. Channel sensing before transmission reduces probability of collision, but does not eliminate it completely, due to the propagation delay along the cable (5 μs). Collision detection allows frame to be cut short as soon as collision is detected, so less time wasted on the channel. No master device required.

Efficiency for Ethernet implementation given as $\eta \approx \frac{T_F}{T_F + 5\tau}$ = 0.998, giving throughput approximately 199 kbit/s.

Example: Polling. Centralised polling needs a master device, sending polling messages to each other device in turn. Devices may only transmit when polled. This eliminates all collisions, so would increase throughput, but also average transfer delay (as have to wait to be polled).

Efficiency estimate requires assumptions about size of polling message, average frame size, whether device polled sends a response to master or just transmits a data frame, how many frames can be transmitted for each poll, etc.

Assuming a polling message of 50 bits, taking 250 μs to transmit. Response is required, of same size. Worst case, with master at one end of cable, average propagation delay between master and polled device is 2.5 μs. This gives latency L = 15.15 ms. (Minimum polling cycle time, with no data sent.)

Assume device may transmit at most one frame when polled. It will transmit with probability $\rho_i = \frac{\lambda_i}{\mu}$, where λ_i is arrival rate at device i and μ is service rate per device, which is one frame per polling cycle. Overall arrival rate is $\lambda = \sum \lambda_i$ frame/s – if the system is operating normally, with stable queues, this is also the overall throughput.

Assume average frame size 2850 bit, giving average frame transmission time $\overline{T_F}$ = 14.25 ms.

Assume the system might operate with average link utilisation ρ_i = 0.8 (for example). Then average cycle time $\overline{t_C} = L + 30\overline{T_F}\rho_i$ = 357.15 ms. Average number of frames sent per cycle is $30\rho_i$ = 24, giving throughput 67.2 block/s or 188.2 kbit/s.

Note that maximum throughput would involve every device transmitting when polled, giving cycle time $\overline{t_C} = L + 30\overline{T_F}$ = 442.65 ms. This would give throughput 67.77 block/s or 189.76 kbit/s. However, this would involve link utilisation of 1, so queues would be unstable – not a practical solution.