(a) (i) Explain the collision detection mechanism applied in standard wired medium access control associated with CSMA and indicate why this might be unsuitable for wireless networks.

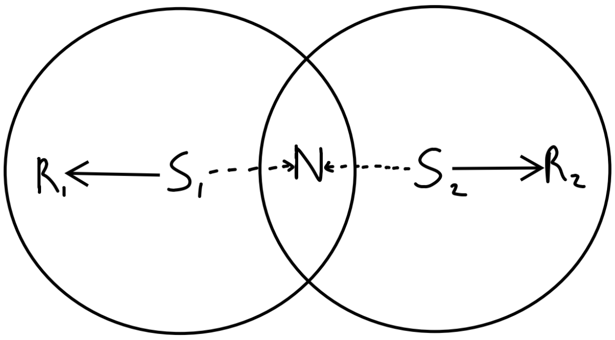
"Carrier Sense Multiple Access / Collision Detection" (CSMA/CD) is the standard wired medium access control. Senders listen on the link to determine whether another node is transmitting on the link. The node waits until the link is idle then transmits their message (Carrier Sense).

If any node detects a collision, they transmit a hash on the network to inform other nodes of the collision. They continue to transmit this hash until they no longer detect the collision. This means frames must be at least $2 \cdot BDP$ such that the sending node is guaranteed to hear of the collision *before* they finish transmitting the packet (to avoid a "late collision"). If the sender is alerted to a collision, they stop transmission and perform a Binary Exponential Backoff before repeating the process.

In Binary Exponential Backoff (BEB), the node starts with a small maximum wait. When BEB is performed, a time is uniformly selected between 0 and the maximum wait. Every time BEB is performed, the maximum wait is doubled.

This protocol struggles with wireless networks. In wireless, we experience local collisions – where one node hears a collision but others do not. So a node may hear a collision and send a jamming signal, preventing all transmission on the network when no node transmitting or receiving data hears the collision.

In the example below, N hears both S_1 and S_2; so transmits a jamming signal telling both to stop transmitting due to a collision. However, neither receivers R_1 or R_2 observe a collision. The critical observation is that *in wireless, collisions happen only at the receivers.*



Furthermore, many (older) devices cannot both listen and transmit on wireless networks at the same time – the signal they send overwhelms their receiver.

(ii) Describe how CSMA/CA (Collision Avoidance) works and explain its limitations.

In CSMA/CA if a node wants to send a message, it waits until the link is idle using Carrier Sense. Once the link is idle, the node sends the data and waits for a response. If the node doesn't receive a response, it performs a Binary Exponential Backoff and repeats.

When using CSMA/CA, the sender must decide how long to wait for a response – if it waits too long, it wastes time. If it's too short it sleeps and unnecessarily retransmits messages.

CSMA/CA suffers from both the hidden and exposed terminal problems. In wireless, signals suffer badly from attenuation and have a range.

In the hidden terminals problem; there may be two senders transmitting to a receiver who can hear both – but both senders are ouf of range of each other so detect no issue. CSMA/CA solves this probabilistically using BEB – it wastes time and bandwidth.

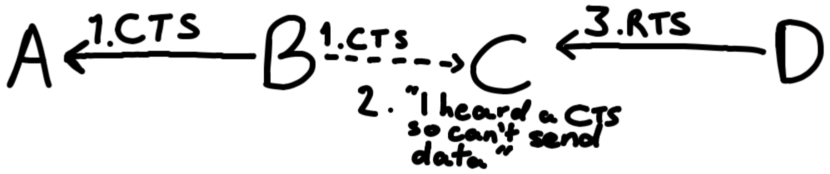
In the exposed terminals problem; a node which wishes to send a message hears a signal so does not transmit – while the receiver is out of range of the signal the sender hears; so it would be safe to send the message.

(iii) Illustrate how MACAW works and indicate its limitations on the exposed terminal problem through an example.

- Nodes wishing to transmit data wait until it will not cause a collision (more later) then send an RTS (request to send)
- If a node hears a RTS for itself and responding would not cause a collision, it responds with a CTS if it is able to safely receive the data.
- Once the sender hears the CTS, it sends the data.
- The receiver sends an acknowledgement ACK once it has received the data.
- If a node hears a RTS for another node, then it is within transmission range of a node which may shortly be receiving data. So it must wait until it would have heard a CTS (using a timeout) before sending any data.
- Once a node hears a CTS, it must defer transmission of data until it hears the ACK.
- Receivers which are in this state are *unable* to respond with a CTS since it would cause a collision.

  So the sender would send an RTS then hear no CTS. This is addressed by the use of an RRTS (request for request to send) – "I heard you wanted to send data but couldn't respond then, lets try again now".

In the exposed terminals problem, a node hears a CTS then a RTS. However, since it heard a CTS, it's not safe for it to send its own CTS. This wastes bandwidth, since it's *safe* for the node wishing to send to transmit.



(iv) Would the deployment of MACAW be needed in an installation of a MAC protocol for a single base station that communicates with some mobile terminals? Why?

No; although it could be used for coordination in a more efficient protocol. MACAW is designed to allow communication to happen concurrently between many nodes over a shared wireless channel. In this system, there are many channels and one node with which each mobile terminal wants to communicate with. This provides an excellent opportunity for a coordinator-based approach allowing mobile terminals to set up channels with the base station. A MACAW-based approach would allow the base station to receive data from at most one node at once – such a system would be unusable (i.e only one person in Cambridge can make a phone call at once).

A better solution would be to multiplex the channel into a number of smaller channels (using FDMA and CDMA) coordinated by the base station. We still have the problem of distributing frequencies and codes to mobile terminals (setting up channels). I propose having a single (or small set of) known channels running the MACAW protocol on which requests to setup channels will be made to the base station.

since the terminals are mobile, they can leave the network. We cannot allocate channels permanently and must therefore have an expiry time for each channel (ie $1h$) with a slightly higher expiry time on the base station (ie $1.5h$) to account for possible clock drift.

However, there could exist "zombie nodes" whose clocks have a very high drift. To resolve this, we *could* run MACAW on each channel – however since this is highly unlikely to occur and MACAW adds high latency to data transmission. A better solution would be to use a modified version of CSMA where sensors listen for $DIFS$ and setup a new channel if they hear a node talking.

(b) (i) You are called upon, as expert, to design a wireless sensor network to monitor environmental factors in a $500m^2$ area within a forest. Sensors will record temperature every 30 minutes. Describe the requirements of the network stack, considering how they differ from a traditional wired or wireless Ethernet.

- The data throughput requirement is very low – a double every 30 minutes.
- The latency requirements are low – we don't mind waiting a few seconds.
- The sensors are wirelessly connected in a forest – there are lots of obstacles and conditions may vary wildly. This could cause a very high error rates.
- The sensor network must support broadcast – sensors do not have accurate timekeeping and so must be synchronised to ensure measurements are taken at the same time.

(ii) Invent two different MAC layer protocols for sensor networks (perhaps simplified versions of SMAC and XMAC) and then indicate which one you would employ for your network and why.

I propose two protocols. The first uses Polling and the second uses a Random Access Protocol. The first protocol has the lowest technology requirements, while the second is built on existing technology.

- The first protocol takes advantage of the latency and bandwidth requirements and uses polling.

  Every 30 minutes, the coordinator broadcasts it's current time and asks all the sensors to synchronise their clocks and record their current reading. The coordinator then polls each of the sensors asking for their most recent reading. Sensors also synchronise when they are polled.

  If Sensors do not hear any synchronise broadcast, they take readings when their clocks are at the time they would take recordings – they then discard this recording once they hear the broadcast.

  This has high latency but uses low bandwidth and has low computational complexity. Each sensor needs only the capability of sending on one channel, and the coordinator needs only to listen or send on one channel at once.

- The second algorithm is based on bluetooth.

  Sensors establish a connection with a coordinator and transmit using spread spectrum and CDMA. Every 30 minutes, the sensors send the base station a signal on their dedicated channel and synchronize their clocks. Since the forest has many obstructions, it's likely to have a high signal-noise ratio and high error rates. Sending using CDMA introduces redundancy and in-built forward error correction (assuming burst errors are unlikely).

  Bluetooth has to deal with hidden and exposed terminals. Since the size of the forest is only $500m^2$, each sensor will be able to hear the other sensors (i.e we won't experience any hidden or exposed terminals). So we could use a CSMA/CD approach. However, once more this adds complexity.

However, the coordinator must be listening on all channels at once all the time. This is computationally expensive.

I would use the polling algorithm. It is simplest and most versatile.

(iii) Read about Directed Diffusion (DD). Explain what you see as its important design features and describe the process through which DD is able to reconfigure when sensor nodes fail in the network.

Directed Diffusion is an iterative method similar to a particle filter: initially flood the network to create a large number of paths from the source to the sink; every time the interest expires, prune the paths most likely to be bad.

In Directed Diffusion, there are sinks, sources, nodes, interests and readings. Nodes are devices on the network. Sinks are nodes which want data. Sources are nodes which generate data. An interest is a message from a sink saying "I want to be notified every time X happens in the next Y seconds".

- When a source wants readings from a sensor, it floods the network with an interest (with an artificially low gradient).
- The *first* time a node receives an interest, it caches and forwards it, recording which node it received the interest from.
- If a sink receives an interest, it starts sending readings from to the nodes it received the interest from at the requested rate until the interest expires.
- When a node receives a reading, it forwards it to all nodes which it received a corresponding interest for that event from.
- When an interest expires, the sink refreshes it but sends messages only to the nodes which it deemed to be "good" (ie low latency/loss rate/corruption). Each intermediate node does the same thing. So every time the interest expires, the number of paths being used decreases.
- Intermediate nodes can aggregate information, reducing the amount of data sent.

  This feels like a "theoretical optimisation" which would actually produce more work – comparing every packet to all other packets to see if any could be aggregated to see if it should be forwarded would be expensive.

When a sensor node fails, the sink can repeatedly "go back one step" until it receives data from another sensor node also capable of fulfilling the interest.