Duplexing and Multiple-Access Techniques

A channel must often be shared between different directions of communication (duplexing) and between different users (multiple access).
After this lecture you should be able to: classify a communication system as full-duplex, half-duplex or simplex; show how time and frequency are divided up between directions and users for TDD, FDD, TDMA, and FDMA; classify multiple-access techniques according to their suitability for constant-rate and bursty data; explain the throughput vs offered load curve for Aloha.

Bands and Channels

The total available radio frequency spectrum is divided by international treaties and national regulators into different frequency *bands* that are allocated to different uses (e.g. terrestrial broadcasting, mobile communications, point-to-point links, military, unlicensed, radar, navigation, etc.).

Each band is further divided up into equal-bandwidth ranges, each of which is a *channel*.

Duplexing

A full duplex communication system allows speech communication in both directions simultaneously while a half-duplex system only allows one person to talk at a time. Systems that send audio in one direction only are called simplex.

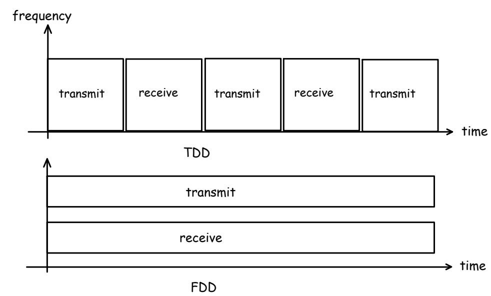
Note that this distinction is from the point of view of the user, not the hardware. As explained below, a full-duplex communication system may not actually transmit and receive simultaneously.

Exercise 1: Is a normal phone call half-duplex, full-duplex or simplex? How about a radio broadcast? A typical police dispatch radio using push-to-talk (PTT)?

Full duplex can be implemented in three different ways:

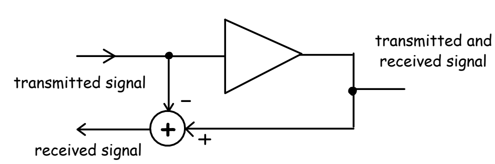
FDD - Frequency Division Duplexing: two frequency ranges are assigned to each call and one is used in each direction. For example the upper frequency is used in one direction and the lower in the other direction. The receivers use filters called "duplexers" that have high attenuation at the transmit frequency but low loss at the receive frequency. FDD is used by most cellular radio systems. This requires "paired" spectrum allocations where each downlink channel is paired with an uplink channel.

TDD - Time Division Duplexing: the two directions alternate transmitting and receiving. For example each side alternately transmits for 4 ms and receives for 4 ms. This technique is possible with digital systems that can digitize and buffer speech. The stored speech is transmitted during assigned transmit time slots.



Many cellular systems use both TDD and FDD. TDD avoids the need for duplexers and FDD reduces the potential for transmissions to interfere with nearby receivers.

Full Duplex [1] - A system that uses the same frequencies at the same time in both directions requires a way to separate out the signals propagating in the two directions. This method has the advantage that the full bandwidth can be used in both directions simultaneously. Here is a simple example:



[1] Note that the term "full duplex" has two meanings. Here "full duplex" refers to a circuit that allows full-duplex operation (a bit confusing).

Circuits or devices that can do this include directional couplers and hybrids. Good cancellation of the transmitted signal requires digital signal processing to accurately estimate and subtract the transmitted signal and its variously-delayed and attenuated echoes.

This method is used by higher-speed voiceband modems and 1 Gb/s Ethernet. It is not practical for wireless systems because the signals received by wireless systems are too weak compared to the transmitted signal level.

Multiple Access

Often the channel must also be shared between different (active) users.

Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) are the two basic ways that a channel can be shared between users.

Carrier-Sense Multiple Access (CSMA) is similar to TDMA and is used to share a channel efficiently when the data is bursty.

Some cellular systems use a technique called CDMA (Code Division Multiple Access) that multiplies each user's signal by a different PN sequence (the "code").

FDMA

FDMA allocates one channel to each user for the duration of a call. Implementing FDMA requires only analog channelization filters and for this reason it was the earliest technique used to divide up the available bandwidth between users.

FDMA is used by all analog wireless systems. This includes many broadcast (radio and TV) and "legacy" two-way radio systems.

Exercise 2: A cable TV system uses frequencies between 100 and 200 MHz and channels are spaced 5 MHz apart. How many simultaneous users can be supported?

TDMA

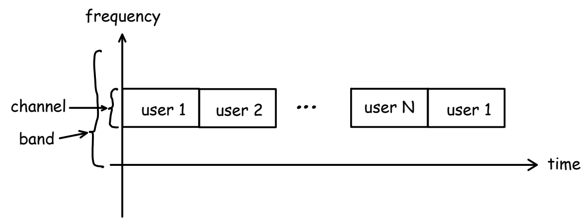
Knuth modulo congruential RNG

TDMA also uses channels, but the capacity of each channel is higher than needed by one user so different users take turns transmitting.

TDMA can only used with digital modulation.

A master station (e.g. cellular base station) coordinates transmissions from different users.

One advantage of TDMA is that filters are not needed to separate users and so the receiver can be simpler and less expensive.



"Guard bands" must be left between channels to allow for uncorrected frequency errors and non-ideal filter responses. "Guard times" must be left between slots to allow for uncorrected propagation delays and transmitter timing uncertainty.

TDMA is used by many multi-user wireless systems such as some second-generation cellular systems (GSM) and many digital broadcast systems.

Exercise 3: GSM cellular systems use FDD and TDMA. Each user gets to transmits 114 bits in one of eight "slots" per frame and each frame lasts is 4.615 ms long. What is the average data rate for each user? GSM channels are spaced every 200 kHz. An operator has one 5 MHz frequency allocation for each direction ("paired" spectrum). How many channels can this operator use?

CSMA

CSMA (Carrier-Sense Multiple Access) is a multiple access technique commonly used for data communication because it provides an efficient sharing of a channel among users that need bursty (infrequent) access to a channel.

A simple variant of CSMA is known as Aloha. Users transmit a frame as soon as it is available. If two users' transmissions overlap they will likely interfere with each other. This "collision" will require that both frames be retransmitted. If the frame is not acknowledged before a time-out period then the sending station waits a random amount of time (the "backoff") before retransmitting the frame. The random backoff minimizes the likelihood of a repeat collision with the same user.

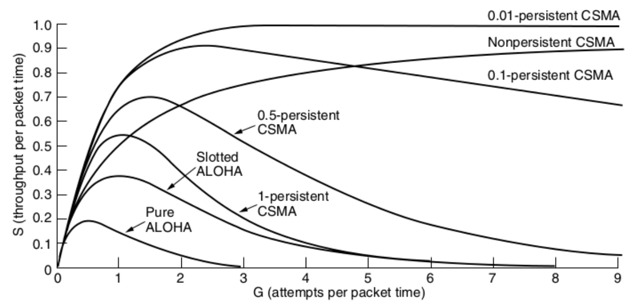
CSMA/CD (CSMA with collision detection) improves on Aloha by having users listen to the channel until the channel is free before transmitting (the "carrier sense" part). Users also listen while transmitting so they can detect when another user is transmitting at the same time and stop transmitting (the "collision detection" part). CSMA/CD thus has higher efficiency and throughput than Aloha. CSMA/CD was the multiple access technique used by the original Ethernet protocol although modern Ethernet systems use point-to-point links rather than a shared channel.

Wireless systems can't detect collisions because of the large difference in transmitted and received signal strengths so they must use different variants of CSMA to improve throughput. For example WiFi system use CSMA/CA (collision avoidance) which involves using short slots for channel access and exponential backoff (explained below) when frames are not acknowledged.

The following graph[2] shows the throughput of various CSMA variants as a function of the total amount of traffic (new data plus retransmissions) presented to the network (the "offered load"). The graph shows original or "pure" Aloha, "slotted" Aloha where time is divided into fixed-length slots, and several versions of CSMA.

All CSMA variants transmit immediately if the channel is free when a frame is first available to transmit. If the channel is busy then the the transmitter must implement a "back off" algorithm. A "non-persistent" protocol waits for a randomly-chosen time each time it finds the channel busy. A "p-persistent" protocol transmits with probability p when the channel is free.

At low offered load the traffic increases linearly for all variants because there are no collisions and nearly all frames transmitted are received. The slope of the curve decreases as the offered load increases because there are more collisions per transmission attempt. For Aloha the throughput actually decreases (and throughput drops to zero) as the offered load increase past a certain point because each collisions results in an increasing number of retransmissions.



Delay, not shown in the diagram above, is often equally important. It typically increases with offered load.

Although retransmissions and backoffs reduce throughput and increase the delay of CSMA compared to TDMA, if the traffic is bursty then many stations will not have traffic to transmit in their time slots and this will result in inefficient use of the channel. Thus CSMA is the preferred multiple-access technique for bursty data sources.

It's also possible to combine the advantages of TDMA and CSMA protocols with a "reservation" technique that divides up the channel time (often also called a "frame" or "superframe") into a reserved (TDMA) portion and a random-access (CSMA) portion. If a device has a lot of data to transmit (e.g. it's transmit buffers are full) a CSMA frame is used to request a time slot allocation within the TDMA portion of the frame. It can then transmit it's packets within that allocation without risk of collisions. This is the multiple access technique used by DOCSIS cable modems, for example.

[2]From *Computer Networks* by Andrew Tanenbaum.