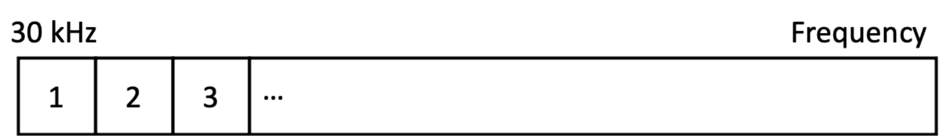
Multiple Access Techniques

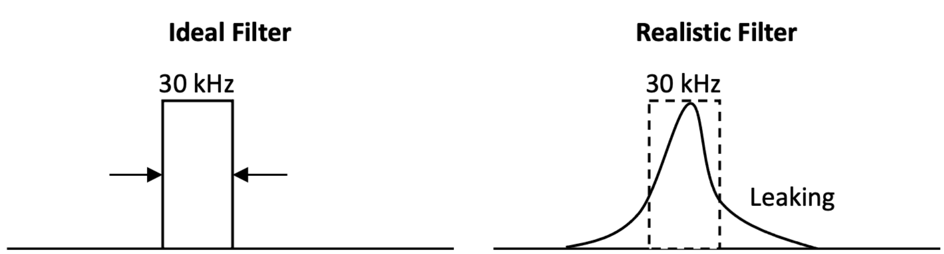
In this lecture, we will make our use of the term "channel" more concrete by discussing the three types found in cellular systems: frequency channels, time slots within frequency bands, and distinct codes. The three corresponding multiple access techniques are frequency-division multiple access (**FDMA**), time-division multiple access (**TDMA**), and code-division multiple access (**CDMA**). Most of our discussion will center around CDMA.

FDMA

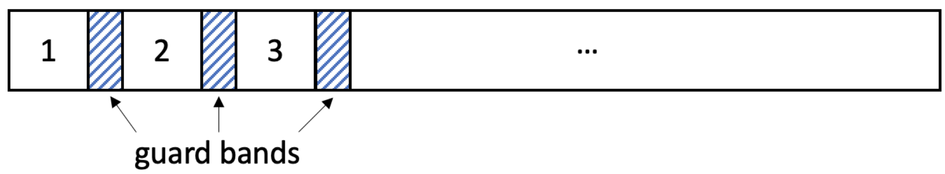
The FDMA scheme, in its simplest form, divides a given frequency band into channels, allocating each to a different system user or mobile terminal. For example, in the 1G AMPS system, 30 kHz channels were assigned to each voice user, which would give a division looking something like this:



In FDMA, the receiver needs to apply a bandpass filter to isolate the channel. Ideally, these filters would have perfectly sharp transitions, but in reality, they experience leakage on either side of the channel:

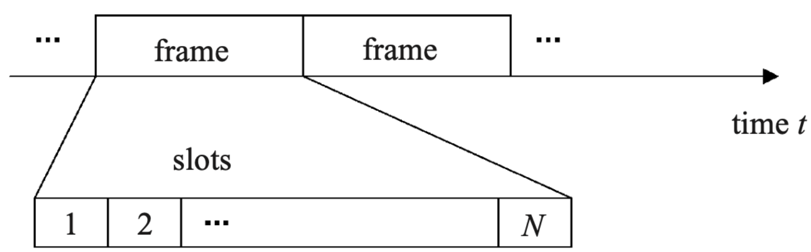


As a result, in FDMA, we need to add **guard bands** at the beginning/end of each channel:



TDMA

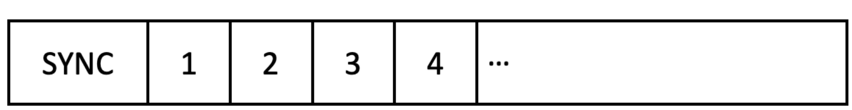
TDMA systems gain capacity improvements over FDMA by assigning multiple users to one frequency channel, separated in time. Digital signals sent out on a given frequency band are transmitted in specified time slots, in a repetitive frame structure:



Each user is assigned to one or more of these time slots per frame. For TDMA to work, both the base station and mobile need to maintain an accurate and identical clock, so that each user can speak with the base station at a specific time.

What is the advantage offered by TDMA?

- Unlike in FDMA, the time slots can be tightly packed, with no need for intervals separating them.
- In reality, some time is used for a synchronization sequence to indicate the start/end of a particular frame, which is essentially a **guard time**:



This synchronization sequence is a code sequence, known to the receiver, so that the receiver knows when data time slots start.

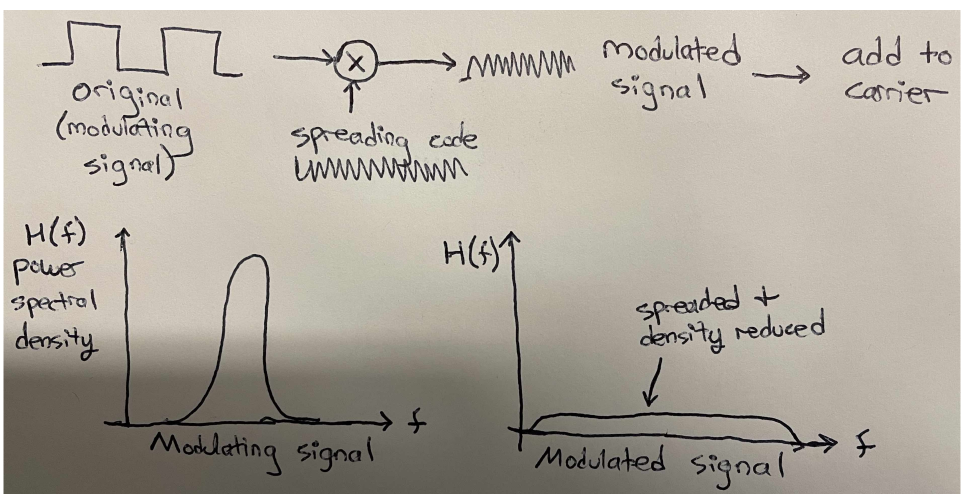
- In a pure TDMA system, the base station only needs one radio, so the cost per user of the cellular infrastructure is lower.

CDMA

The third multi-access technology, which first appeared in 2G cellular, is CDMA. CDMA is based on **spread-spectrum** technologies, which were invented and developed originally for military communication systems.

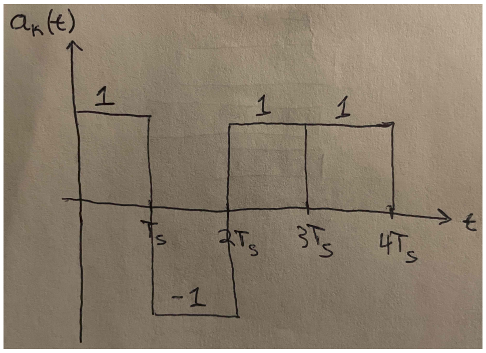
Spread-spectrum modulations refer to any modulation technique in which the bandwidth of the **modulated signal** (i.e., the signal transmitted over the air) is much larger than that of the **modulating signal** (i.e., the information we are sending).

Direct Sequence-Spread Spectrum (**DS-SS**) is one such modulation technique, where a **pseudo-random sequence** functions as the **spreading code**, modulating each bit of information to be transmitted. The process is as follows, where the multiplication by the spreading code occurs bit by bit:



With "good" spreading codes (pseudo-random sequences), the modulated signal will look like random background noise. This has special significance in military applications, as it allows stealthy communication. We will be focusing more on the capacity aspect of CDMA.

To be more precise, consider a binary signal $a_k(t) \in \{-1, 1\}$ that we are aiming to transmit, with a symbol duration T_s. For example:



First, we will introduce the case without a spreading sequence. In normal binary phase shift keying (**BPSK**), the transmitted signal becomes

$$s_d(t) = \sqrt{2P}\cos(\omega_0 t) \cdot a_k(t), \tag{1}$$

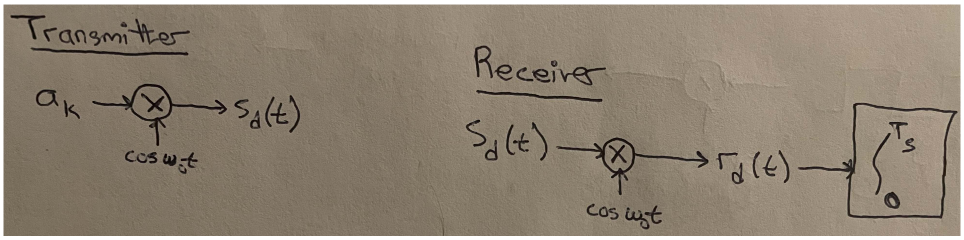
where P is the total power of the transmission, $\cos(\omega_0 t)$ is the carrier, and $a_k(t)$ provides a phase modulation of 0 or π: $s_d(t) = \sqrt{2P}\cos(\omega_0 t)$ when $a_k(t) = 1$, and $s_d(t) = \sqrt{2P}\cos(\omega_0 t + \pi)$ when $a_k(t) = -1$. At the receiver, the signal is multiplied by the carrier for demodulation:

$$r_d(t) = \sqrt{2P}\cos^2(\omega_0 t) \cdot a_k(t), \tag{2}$$

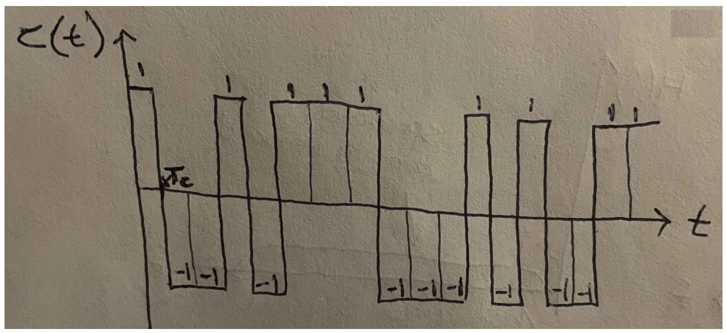
and the transmitted signal can be recovered by integrating $r_d(t)$ over the symbol period:

$$\int_0^{T_s} r_d(t)\, dt = a_k(t) \cdot \underbrace{\int_0^{T_s} \sqrt{2P}\cos^2(\omega_0 t)\, dt}_{\text{constant}>0}. \tag{3}$$

This process is summarized in the figure below:



Now, suppose we add a spreading sequence $c(t) \in \{-1, 1\}$. This spreading sequence will be pseudo-random: it has random/noise-like properties, but ultimately can be recreated at the receiver. The **chip duration** T_c is the duration of each bit in $c(t)$, with each bit referred to as a chip. In general, $T_c \ll T_s$ to create the spreading effect. $c(t)$ thus may look something like this:



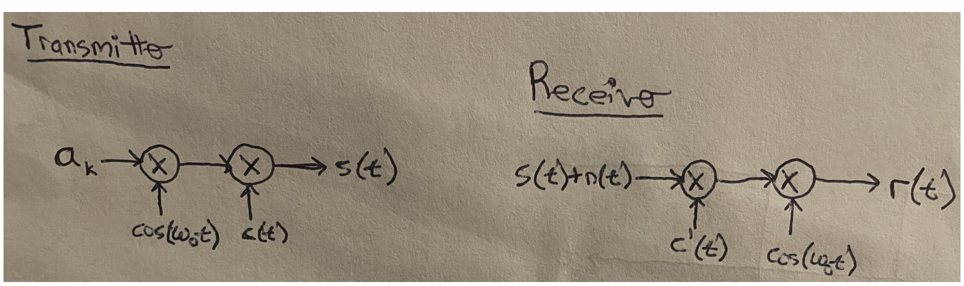
The spreading sequence will multiply $a_k(t)$ bit-by-bit, creating the following transmit signal:

$$s(t) = \sqrt{2P}\cos(\omega_0 t) \cdot a_k(t) \cdot c(t). \tag{4}$$

The receiver, then, will multiply $s(t)$ (plus some added noise $n(t)$) by a spreading code $c'(t)$, and by the carrier, which gives the following receive signal:

$$r(t) = \sqrt{2P}\cos^2(\omega_0 t) \cdot c(t) \cdot c'(t) \cdot a_k(t) + n'(t). \tag{5}$$

This process is summarized in the following figure:



To see how CDMA works, we consider two cases of transmit signals appearing at the receiver.

Case (1): $c(t) = c'(t)$. First, consider that the same spreading code is used at the transmitter and receiver, with perfect synchronization. In this case,

$c(t)c'(t) = 1$ for all t, and (5) becomes

$$r(t) = \sqrt{2P}\cos^2(\omega_0 t) \cdot a_k(t) + n'(t). \tag{6}$$

In this case, there is no spreading effect at the receiver. As in (2), $r(t)$ is then fed to the detector to retrieve $a_k(t)$.

We also make note of the bandwidths of the different signals:

- The modulating signal $a_k(t)$, with a symbol rate T_s, has bandwidth $B_s = 1/T_s$. $s_d(t)$, i.e., the transmit signal without spreading, will have the same bandwidth.
- The transmitted signal $s(t)$, with a chip rate $T_c \ll T_s$, has a bandwidth $B_c = 1/T_c \gg B_s$. At the same total power P, the power spectral density (PSD) of the modulated signal is a much broader and scaled down (by a factor W) version of the modulating signal.
- At the receiver, since $c'(t) = c(t)$, then the bandwidth of $r(t)$ is still B_s.

Case (2): Another user with $\tilde{c}(t) \neq c(t)$. Consider instead the transmission from another user that has a different spreading code $\tilde{c}(t)$:

$$\tilde{s}(t) = \sqrt{2P}\cos(\omega_0 t) \cdot \tilde{a}_k(t) \cdot \tilde{c}(t). \tag{7}$$

At the receiver from case (1), $\tilde{s}(t)$ is an interferer. The interfering signal is obtained as

$$\tilde{r}(t) = \sqrt{2P}\cos^2(\omega_0 t) \cdot \tilde{c}(t) \cdot c(t) \cdot \tilde{a}_k(t) + n'(t). \tag{8}$$

Since $\tilde{c}(t) \neq c(t)$, $\tilde{r}(t)$ looks like another pseudo-random sequence at this receiver. In fact, if $c(t)$ and $\tilde{c}(t)$ are chosen to be perfectly **orthogonal**, then we would have

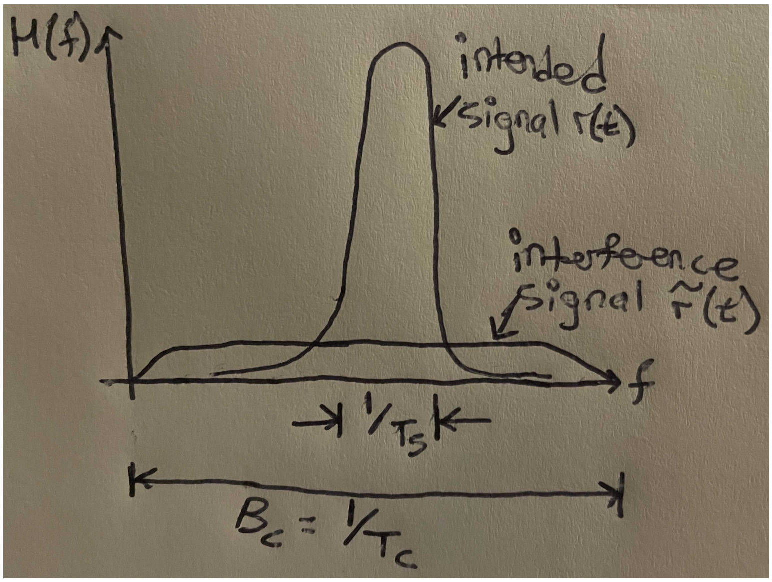
$$\int_0^{T_s} c(t)\tilde{c}(t)dt = 0 \tag{9}$$

at the receiver, and there would be no interference caused by $\tilde{r}(t)$ at all. However, the number of orthogonal codes is small, so the pseudo-random interference case is more likely to be encountered. Additionally, the orthogonality property can be lost if the synchronization is off, as we saw with OFDMA.

With a pseudo-random interference signal, $\tilde{r}(t)$ will have a much wider bandwidth than $r(t)$ from case (1):

- The bandwidth of $\tilde{r}(t)$ is $B_c \gg B_s$.

Qualitatively, the difference between the PSDs will be as follows:



When we apply a bandpass filter with bandwidth $B_s = 1/T_s$, the power of the interfering signal is reduced to

$$P \cdot \frac{1/T_s}{1/T_c} = \frac{P}{W}, \tag{10}$$

where $W = T_s/T_c$ is the **processing gain** of CDMA. If W is large, the receiver will be able to decode even when two CDMA users transmit simultaneously. In this way, each "code" serves as a channel: a user can successfully communicate provided that the same code is not used by other users in the same cell.

Ultimately, the number of codes that can be created is finite. Even if we had an infinite number of codes, does that mean CDMA could support an infinite number of channels? No. We have to consider the resulting SINR at the receiver. Assuming the received signal strength is equalized to P,

$$\text{SINR} = \frac{P}{\frac{P}{W}(N-1) + \eta}, \tag{11}$$

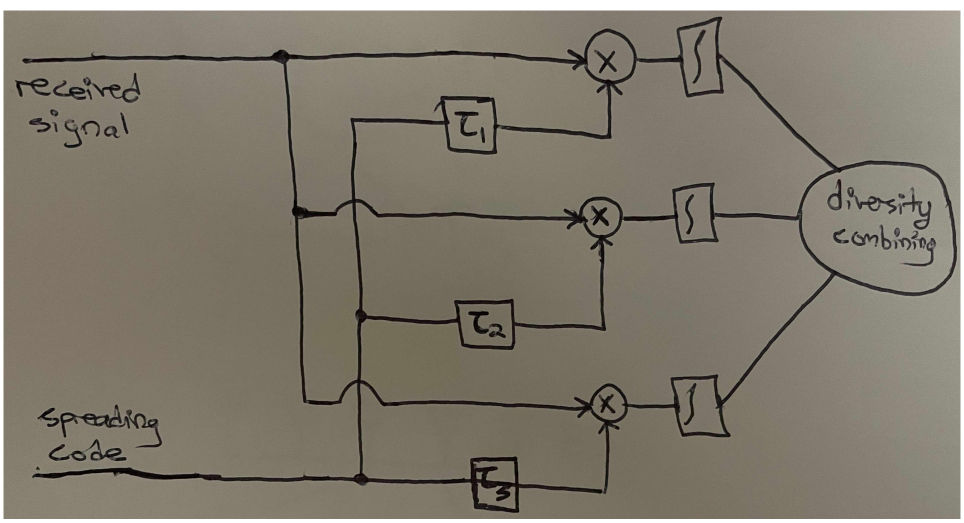
where N is the number of users, and η is the background noise. The number of users N that can be supported depends on the required SINR level. Importantly, we see that the number of available channels in CDMA systems is limited by interference, rather than by the reuse pattern as in FDMA/TDMA.

For example, in the IS-95 standard, each frequency channel is 1.25 MHz, the chip sequence is 1.2288 Mcps, and the data sequence is 19.2 kbps. This gives a processing gain of 1228.8/19.2 = 64.

RAKE Receiver

Recall that we introduced the RAKE receiver in our discussion of channel fading. RAKE is a solution for resolving individual multipath rays in wideband systems when the delay spread is much greater than the symbol period. In particular, in CDMA, the bandwidth of the signal tends to be much larger than the coherence bandwidth, in which case different paths can be separately detected. Multiple detected paths can be combined to achieve a higher SINR.

We can consider a receiver design as follows:



In this way, the RAKE receiver in CDMA exploits the fact that individually resolvable path of the signal will have maximum correlation with the spreading code at a particular delay. Diversity combining can pick either the maximum path, or some weighted sum of the paths that maximizes the SINR.