

# Selecting Mixed Signal Components for Digital Communication Systems—Sharing the Channel

by Dave Robertson

Part I provided an introduction to the concept of channel capacity—and its dependence on bandwidth and SNR; Part II gave a brief summary of different types of modulation schemes. This segment discusses communications signal-processing issues that arise when multiple users share the same transmission medium.

## SHARING THE CHANNEL

Selection of an appropriate modulation scheme is only part of the problem of defining a communications network. In most cases, the transmission medium must accommodate signals from more than a single transmitter. The most obvious case of such multiple use is the airwaves; they must carry a variety of wireless traffic, from broadcast radio and television, to cellular telephony, to CB and short-wave radio. Even a simple twisted-pair telephone wire, which represents a dedicated line between the phone company central office and a user, must carry both incoming and outgoing voice and data during a call.

In most cases, the key to effective multiplexing of independent transmissions is proper observance of “live and let live” protocols, enabling the effective transmission of the desired message without undue interference to other transmissions. There are a variety of approaches towards sharing a communications medium among multiple users; each has its own requirements affecting component selection. Most of these schemes are usable for both analog and digital communications; but the flexibility of time compression, and other features available in digital communications, opens up more options.

**TDMA—time-division multiple access:** perhaps the most obvious way of sharing the communications channel is to “take turns”: only one transmitter at a time is allocated the channel. There must of course be some sort of protocol to establish who has the transmission privilege, when, how often, and for how long. A simple example is the walkie-talkie user’s employment of the word “over” to indicate the termination of a transmission stream and freeing up the communications channel for other users to transmit.

A more formal arrangement is usually desirable, especially when each user is to be allotted a very brief—but repetitive—participation. An overall time period can be divided into designated “slots”, with each of the transmitters assigned a different time slot for transmission (Figure 1). This kind of scheme requires synchronization of all the transmitters, plus a “supervisor” to assign time slots as new transmitters want to enter the channel—and to keep track of slots vacated. Some “overhead” space must be provided to allow for transitions between transmitter time slots; the better the synchronization, the less time lost to these transition periods. Time multiplexing also means that the stream of data

from a given transmitter is not continuous, but in bursts. To represent a continuous conversation (say in a cellular phone call), the digitized information acquired during the period between transmissions must be time compressed, transmitted in a short burst, then expanded in the receiver to form a transparently continuous message.

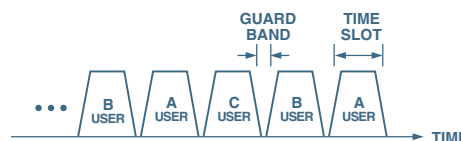


Figure 1. Illustration of time multiplexing, showing guard bands.

The analogy of a panel discussion is sometimes used to illustrate the nature of TDMA. A participant who interrupts out of turn or rattles on and on endlessly commits “violations of the TDMA protocol.” The European GSM digital cellular telephony standard makes use of TDMA; each channel carries eight phone calls simultaneously in a repeated transmitting sequence of eight time slots.

Component selection for TDMA systems must involve careful consideration of bandwidths and settling times; long time constants of components with insufficient bandwidth will tend to cause signals to “bleed into” an adjacent user’s time slot.

**FDMA—frequency-division multiple access:** anyone who receives TV or radio broadcasts at home is familiar with an example of frequency-division multiple access. In this case, multiple transmitters can simultaneously transmit without interference (at a given power level in a given geographical area) by keeping each frequency in their transmissions within a designated frequency slot. The receiver determines which channel is to be recovered by tuning to the desired frequency slot. It is important that each transmitter’s frequency limits be strictly observed; any transgressions would create interference in the neighboring channels. (Figure 2)

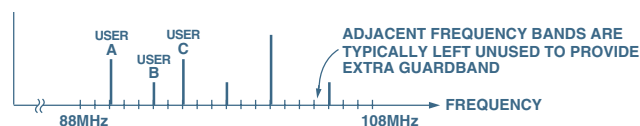


Figure 2. Illustration of frequency multiplexing, showing unused frequency bands to provide separation.

Using the conversational analogy, this might be like providing a set of booths, one for each speaker; if they speak quietly enough, all “transmitters” can broadcast simultaneously, and a listener may “tune in” by listening at the desired booth.

Almost all wireless applications are subject to frequency band constraints; national and international regulatory bodies, e.g., the FCC in the United States, license the transmitter to specific frequencies or restrict its class to specific bands. Wired applications like cable TV also use frequency separation to allow simultaneous transmission of hundreds of channels (both analog and digital).

Keeping within the specified frequency constraints has numerous ramifications for component selection. For example, some component in the system will be used as a precise frequency reference. It could be an absolute frequency reference, like a crystal,

or it might contain a circuit that receives and “locks on” to an external reference frequency. Components in the transmission path must have carefully limited spectral content; this can be done through filtering—but it is also necessary to control component linearity, so as not to generate incidental “out of band” harmonics and other spurious frequency components.

**CDMA—Carrier Division Multiple Access**—Continuing the conversation analogies, suppose that 10 people are trying to carry on 5 simultaneous one-on-one conversations in a small room. Suppose further that one pair agrees to converse in English, another in French, the others in Chinese, Finnish, and Arabic—and all are monolingual. If you were a member of the English speaking pair, you would hear a din of background “babble”, but the only intelligible information would be in English. So it’s easy to see that all 5 conversations could take place simultaneously in the same room (though in practice, everyone would probably get a headache).

This is essentially a description of the underlying idea of carrier division multiple access. All users transmit and receive over the same frequency band, but each pair is assigned a unique code sequence. The digital bit stream you wish to send is modulated with this unique code sequence and transmitted. A receiver will receive the combined modulated bit streams of all the transmitters. If the receiver demodulates this composite signal with the same unique code, it essentially performs a cross-correlation operation: the bit stream that was modulated with the same code sequence will be recovered; all the other transmitted signals that were modulated with different codes will be rejected as “noise”.

Modulation with the special code tends to spread the spectrum of the initial digital bit stream over a much wider bandwidth, which helps improve its immunity from interference. Despite this spectral spreading, spectral efficiency can be maintained, because multiple users can share the same bandwidth. Adding more users simply leads to the appearance of increased noise in the channel

Examples of CDMA systems include the IS95 Digital Cellular standard in the US and numerous military “spread spectrum” communications applications (an additional advantage of modulating the transmitted signal with a unique signal is that it is essentially encrypted; a receiver cannot recover the transmitted message without the unique modulation sequence). Though CDMA systems involve greater digital complexity, the performance requirements for their analog components are reduced. However, because multiple transmitters will be broadcasting in the same channel at the same time, it is usually desirable to minimize the contributions to background and spurious noise by transmitter components.

**SDMA—Space Division Multiple Access:** Returning to the conversation analogy, another way to carry on simultaneous one-on-one conversations in the same room is to move to opposite corners of the room and speak in relatively hushed tones. This captures the spirit of SDMA. In wireless applications, signal strength falls off rapidly with increasing distance from the transmitting antenna. At a great enough distance, the signal can be considered to have faded completely, from which point a new transmitter could reuse the same frequency or time slot for a different signal (Figure 3). In broadcast radio, the same frequency can be reused in different cities, provided that they are far enough apart.\*

\*The attenuation of signal with distance is a strong function of frequency: The higher the transmitter frequency, the faster the rolloff.

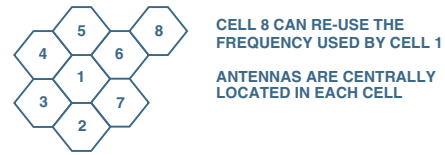


Figure 3. Illustration of geographical multiplexing, showing honeycomb of cells with base-station antennas at centers.

The concept of channel re-use with distance underlies the term “cellular telephony.” Cell size is determined by the area of effective coverage by a given transmitter, and the same frequencies can be reused in other cells. In practice, however, patterns are designed so that adjacent cells will not re-use the same frequencies. Conventional antennas radiate in all directions, producing a circular coverage area and the “honeycomb” cellular pattern in Figure 3. Modern technology has added new dimensions to the concept of SDMA with the development of focused, or beam steering antennas. Phased-array technology can create a focused, directional signal transmission pattern aimed at either an individual target receiver or a particular target area (e.g., a specific highway at rush hour). This can allow more rapid re-use of frequency spectrum, thereby effectively increasing total capacity for wireless applications.

Advanced digital communications systems use combinations of these multiplexing schemes to effectively pack as much capacity as possible into the available transmission channel. For example, GSM cellular phones use TDMA, FDMA and SDMA to allocate traffic. Even many wired applications make use of TDMA and FDMA protocols. Although these multiplexing arrangements typically add to the system complexity, the effective increase in channel capacity more than offsets increases in component cost.

### THE NEAR/FAR PROBLEM

In previous installments, we have discussed the impact of error rate and modulation scheme on the required dynamic range in a digital communications system. However, in many applications, the *multiplexing* arrangements create the ultimate demands on dynamic range in the communications receiver.

In any application, the strength of the received signal is a function of the strength of the transmitted signal, the distance from the transmitter, and numerous environmental factors relating to the transmission medium (be it wireless or wired). Most communications systems are designed to work over a variety of distances, and so have to be designed to accommodate a large variation in power of the received signal.

Consider, for example, a cellular telephony application. The receiver circuitry must be designed to recover the weak signal resulting from a transmission while at the very edge of the “cell”. This capability to recover weak signals is often referred to as a receiver’s *sensitivity*. To recover such weak signals, it seems appropriate to include gain stages in the receive circuitry. Consistent with good, low-noise design practice, one might expect to put the gain as early in the signal path as possible to quickly boost the signal above the noise floor of subsequent stages.

Unfortunately, this same receiver must also be capable of receiving the signal transmitted by a user standing directly under the base station’s antenna. In the case of GSM, for example, this signal can be up to 90 dB stronger than the weakest signal. If the receiver

has too much gain in the signal path, the strong signal can saturate the gain stages. For modulation schemes that include amplitude information (including AM and QAM), this will essentially destroy the signal. Phase and frequency modulation approaches may be more tolerant of this clipping, depending on the circumstances. (The clipping will still create distortion products which are sufficient to cause problems, even in phase-modulation schemes.)

A basic approach to addressing the near/far dynamic range problem is to use variable/programmable gain stages in the receive signal path. Automatic gain control (AGC) allows the gain to be adjusted in response to the strength of the received signal. An important design consideration, though, is how rapidly the gain needs to be adjusted. For example, in ADSL (asymmetric digital subscriber line—see sidebar) modems, the received signal strength changes as outdoor temperature changes affect the line impedance, so time constants of minutes would be tolerable. On the other hand cellular phone receivers must be designed to track the signals from fast moving vehicles that may be moving into or emerging from the shadows of buildings or other signal obstacles, so very rapid gain changes are required. TDMA systems put an additional demand on gain-ranging circuitry, because the near/far signals could be located in adjacent TDMA time slots; in this case, the circuitry would have to change gains and settle in the transition period between time slots.

FDMA systems offer a different kind of near/far challenge. Here, the worst case to consider is recovery of a weak signal in a frequency slot next to strong signal (Figure 4). Since both signals are present simultaneously as a composite at the input of a gain stage, the gain is set according to the level of the stronger signal; the weak signal could be lost in the noise floor (in this case, the noise floor could be thermal noise or quantization noise of an A/D converter.)

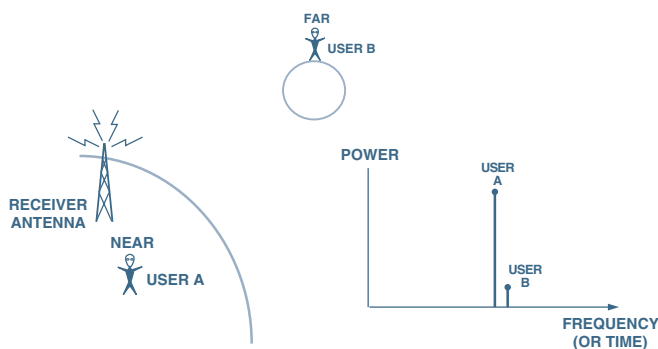


Figure 4. Near-far effect calls for the ability to handle wide dynamic range between adjacent channels.

Even if subsequent stages have a low enough noise floor to provide dynamic range to recover the weak signal, there must also be a very stringent constraint on the dynamic linearity of the gain stage; harmonics or other spurious responses of the strong signal that wind up in the wrong frequency bin could easily obliterate the weaker desired signal. To reduce this interference problem, most FDMA systems attempt to filter out unwanted signals early in the receive circuitry. The ability to discriminate against unwanted signals in adjacent frequency bands is usually referred to as a receiver's *selectivity*.

Most radio designs feature a cascaded series of filters and gain stages (some of which may be variable) to remove/attenuate strong interferers, then amplify the desired signal to a level that can be readily demodulated. Wideband radios, however, attempt to simultaneously recover all the signals in one receiver; they cannot use analog discrimination filters; accordingly, wideband receivers typically have the most stringent requirements on dynamic range in their analog circuitry and converters. Interestingly enough, even applications where you think you have the communications channel to yourself can suffer from simultaneous near/far signals. For example, in ADSL modems, the system must be designed for the scenario where the near-end echo (leakage from the local transmitter) appears as an interfering signal that is actually up to 60 dB stronger than the desired receive signal.

In CDMA systems the near/far problem is a little more difficult to describe. Since all signals are simultaneously transmitted in the same frequency space, filtering cannot be used to discriminate against unwanted signals (though it is still used to eliminate signals in adjacent bands). CDMA employs demodulation using a carrier unique to the desired signal to extract the desired from the unwanted signals; signals modulated with a different carrier appear as background noise. The ability to successfully recover the signal is set by the total noise energy—including that of the other carriers—in the band. Since filtering can't be used to discriminate, the best situation to strive for is to have all signals arrive at the base-station antenna at equal power. To achieve this, many CDMA systems communicate the received power levels back to the transmitters so that power of the individual signal components may be adjusted to equalize power levels at the base-station receiver. To help reduce their near/far problem, TDMA systems could also use this kind of power control, though it tends to require a more-sophisticated (i.e., costly) handset. ▶

### ASYMMETRIC DIGITAL SUBSCRIBER LINE

ADSL is one of the many technologies competing to bring broadband digital services into the home. The concept underlying ADSL is to take advantage of the twisted-pair wires that already provide almost universal telephone service to homes in the United States. Other services providing a two-way flow of information, such as ISDN (integrated services digital network), require an additional, dedicated wire to provide service.

ADSL uses frequency-division multiplexing (FDM) to convey modulated digital information in the frequency space between 20 kHz and 1.2 MHz, above the frequency space occupied by conventional voice traffic. This frequency separation allows an ADSL modem to operate without disturbing a phone call occurring at the same time—an extremely important feature.

The ANSI standard for ADSL provides for simultaneous upstream (outgoing from the home) and downstream (incoming to the home) transmission using either FDM (separating the upstream and downstream signals in frequency) or echo cancelling. Echo cancelling uses sophisticated signal processing (analog, digital, or both) to separate the strong transmitted signal from the weaker received signal, passing only the received signal to the demodulator. Using the conversational model, this is analogous to a person who can effectively talk and listen at the same time.