# Theory & Applications of Discrete Time Signal Processing

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## Abstract

DSP is concerned with the representation of the signals by a sequence of numbers or symbols and the processing of these signals. Digital signal processing and analog signal processing are subfields of signal processing. DSP includes subfields like: audio and speech signal processing, sonar and radar signal processing, sensor array processing, spectral estimation, statistical signal processing, digital image processing, signal processing for communications, biomedical signal processing, seismic data processing, etc.

## Keywords

Signal Processing, Speech Processing, Pattern recognition, Image Processing, Face Detection, Feature Detection

## 1. Introduction

**Digital signal processing** (**DSP**) DSP is concerned with the representation of the signals by a sequence of numbers or symbols and the processing of these signals Since the goal of DSP is usually to measure or filter continuous real-world analog signals, the first step is usually to convert the signal from an analog to a digital form, by using an analog to digital converter. Often, the required output signal is another analog output signal, which requires a digital to analog converter.

DSP algorithms have long been run on standard computers, on specialized processors called digital signal processors (DSPs), or on purpose-built hardware such as application-specific integrated circuit (ASICs). Today there are additional technologies used for digital signal processing including more powerful general purpose microprocessors, field-programmable gate arrays (FPGAs), digital signal controllers (mostly for industrial apps such as motor control), and stream processors, among others.

## 2. DSP domains

In DSP, engineers usually study digital signals in one of the following domains: time domain (one-dimensional signals), spatial domain (multidimensional signals), frequency domain, autocorrelation domain, and wavelet domains. They choose the domain in which to process a signal by making an informed guess (or by trying different possibilities) as to which domain best represents the essential characteristics of the signal. A sequence of samples from a measuring device produces a time or spatial domain representation, whereas a discrete Fourier transform produces the frequency domain information, that is the frequency spectrum. Autocorrelation is defined as the cross-correlation of the signal with itself over varying intervals of time or space.

## 3. Signal sampling

With the increasing use of computers the usage of and need for digital signal processing has increased. In order to use an analog signal on a computer it must be digitized with an analog to digital converter (**ADC**). Sampling is usually carried out in two stages, discretization and quantization. In the discretization stage, the space of signals is partitioned into equivalence classes and quantization is carried out by replacing the signal with representative signal of the corresponding equivalence class. In the quantization stage the representative signal values are approximated by values from a finite set.

In order for a sampled analog signal to be exactly reconstructed, the Nyquist-Shannon sampling theorem must be satisfied. This theorem states that the sampling frequency must be greater than twice the bandwidth of the signal. In practice, the sampling frequency is often significantly more than twice the required bandwidth. The most common bandwidth scenarios are: DC - $BW_x$ (baseband); and $F_c$ +/-$BW_x$, a frequency band centered on a carrier frequency ("direct demodulation").

A digital to analog converter (DAC) is used to convert the digital signal back to analog. The use of a digital computer is a key ingredient in digital control systems.

## 4. Time and space domains

The most common processing approach in the time or space domain is enhancement of the input signal through a method called filtering. Filtering generally consists of some transformation of a number of surrounding samples around the current sample of the input or output signal. There are various ways to characterize filters; for example:

- A "linear" filter is a linear transformation of input samples; other filters are "non-linear." Linear filters satisfy the superposition condition, i.e. if an input is a weighted linear combination of different signals, the output is an equally weighted linear combination of the corresponding output signals.

- A "causal" filter uses only previous samples of the input or output signals; while a "non-causal" filter uses future input samples. A non-causal filter can usually be changed into a causal filter by adding a delay to it.

- A "time-invariant" filter has constant properties over time; other filters such as adaptive filters change in time.

- Some filters are "stable", others are "unstable". A stable filter produces an output that converges to a constant value with time, or remains bounded within a finite interval. An unstable filter produces output which diverges.

- A "finite impulse response" (FIR) filter uses only the input signal, while an "infinite impulse response" filter (IIR) uses both the input signal and previous samples of the output signal. FIR filters are always stable, while IIR filters may be unstable.

Most filters can be described in Z-domain (a superset of the frequency domain) by their transfer functions. A filter may also be described as a difference equation, a collection of zeroes and poles or, if it is an FIR filter, an impulse response or step response. The output of an FIR filter to any given input may be calculated by convolving the input signal with the impulse response. Filters can also be represented by block diagrams which can then be used to derive a sample processing algorithm to implement the filter using hardware instructions.

## 5. Frequency domain

Signals are converted from time or space domain to the frequency domain usually through the Fourier transform. The Fourier transform converts the signal information to a magnitude and phase component of each frequency. Often the Fourier transform is converted to the power spectrum, which is the magnitude of each frequency component squared.

The most common purpose for analysis of signals in the frequency domain is analysis of signal properties. The engineer can study the spectrum to determine which frequencies are present in the input signal and which are missing.

Filtering, particularly in non realtime work can also be achieved by converting to the frequency domain, applying the filter and then converting back to the time domain. This is a fast, O(n log

n) operation, and can give essentially any filter shape including excellent approximations to brickwall filters.

There are some commonly used frequency domain transformations. For example, the cepstrum converts a signal to the frequency domain through Fourier transform, takes the logarithm, then applies another Fourier transform. This emphasizes the frequency components with smaller magnitude while retaining the order of magnitudes of frequency components.

Frequency domain analysis is also called *spectrum*- or *spectral analysis*.

## 6. Applications

The main applications of DSP are audio signal processing, audio compression, digital image processing, video compression, speech processing, speech recognition, digital communications, RADAR, SONAR, seismology, and biomedicine. Specific examples are speech compression and transmission in digital mobile phones, room matching equalization of sound in Hifi and sound reinforcement applications, weather forecasting, economic forecasting, seismic data processing, analysis and control of industrial processes, computer-generated animations in movies, medical imaging such as CAT scans and MRI, image manipulation, high fidelity loudspeaker crossovers and equalization, and audio effects for use with electric guitar amplifiers.

## 7. Related Work

Digital signal processing is often implemented using specialised microprocessors such as the DSP56000 and the TMS320. These often process data using fixed-point arithmetic, although some versions are available which use floating point arithmetic and are more powerful. For faster applications FPGAs might be used. Beginning in 2007, multicore implementations of DSPs have started to emerge from companies including Freescale and startup Stream Processors, Inc. For faster applications with vast usage, ASICs might be designed specifically. For slow applications such as flame scanning, a traditional slower processor such as a microcontroller can cope.

**7.1 Analog signal processing** is any signal processing conducted on analog signals by analog means. "Analog" indicates something that is mathematically represented as a set of continuous values. This differs from "digital" which uses a series of discrete quantities to represent signal. Analog values are typically represented as a voltage, electric current, or electric charge around components in the electronic devices. An error or noise affecting such physical quantities will result in a corresponding error in the signals represented by such physical quantities.

Examples of analog signal processing include crossover filters in loudspeakers, "bass", "treble" and "volume" controls on stereos, and "tint" controls on TVs. Common analog processing elements include capacitors, resistors, inductors and transistors

### *7.2* Telecommunication

Alexander Graham Bell's original telephone, at the *Musée des Arts et Métiers* in Paris

**Telecommunication** is the assisted transmission of signals over a distance for the purpose of communication. In earlier times, this may have involved the use of smoke signals, drums, semaphore, flags, or heliograph. In modern times, telecommunication typically involves the use of electronic transmitters such as the telephone, television, radio or computer. Early inventors in the field of telecommunication include Antonio Meucci, Alexander Graham Bell, Guglielmo Marconi and John Logie Baird. Telecommunication is an important part of the world economy and the telecommunication industry's revenue has been placed at just under 3 percent of the gross world product.

## 8. Basic elements

A telecommunication system consists of three basic elements:

-a transmitter that takes information and converts it to a signal;

-a transmission medium that carries the signal; and,

-a receiver that receives the signal and converts it back into usable information.

For example, in a radio broadcast the broadcast tower is the transmitter, free space is the transmission medium and the radio is the receiver. Often telecommunication systems are two-way with a single device acting as both a transmitter and receiver or *transceiver*. For example, a mobile phone is a transceiver.

Telecommunication over a phone line is called point-to-point communication because it is between one transmitter and one receiver. Telecommunication through radio broadcasts is called broadcast communication because it is between one powerful transmitter and numerous receivers.

**Analogue or digital**

Signals can be either analogue or digital. In an analogue signal, the signal is varied continuously with respect to the information. In a digital signal, the information is encoded as a set of discrete values (for example ones and zeros). During transmission the information contained in analogue signals will be degraded by noise. Conversely, unless the noise exceeds a certain threshold, the information contained in digital signals will remain intact. This noise resistance represents a key advantage of digital signals over analogue signals.

**Networks**

A collection of transmitters, receivers or transceivers that communicate with each other is known as a network. Digital networks may consist of one or more routers that route information to the correct user. An analogue network may consist of one or more switches that establish a connection between two or more users. For both types of network, repeaters may be necessary to amplify or recreate the signal when it is being transmitted over long distances. This is to combat attenuation that can render the signal indistinguishable from noise.

**Channels**

A channel is a division in a transmission medium so that it can be used to send multiple streams of information. For example, a radio station may broadcast at 96.1 MHz while another radio station may broadcast at 94.5 MHz. In this case, the medium has been divided by frequency and each channel has received a separate frequency to broadcast on. Alternatively, one could allocate each channel a recurring segment of time over which to broadcast—this is known as time-division multiplexing and is sometimes used in digital communication.

**Modulation**

The shaping of a signal to convey information is known as modulation. Modulation can be used to represent a digital message as an analogue waveform. This is known as keying and several keying techniques exist (these include phase-shift keying, frequency-shift keying and amplitude-shift keying). Bluetooth, for example, uses phase-shift keying to exchange information between devices.

Modulation can also be used to transmit the information of analogue signals at higher frequencies. This is helpful because low-frequency analogue signals cannot be effectively transmitted over free space. Hence the information from a low-frequency analogue signal must be superimposed on a higher-frequency signal (known as a carrier wave) before transmission. There are several different modulation schemes available to achieve this (two of the most basic being amplitude modulation and frequency modulation). An example of this process is a DJ's voice being superimposed on a 96 MHz carrier wave using frequency modulation (the voice would then be received on a radio as the channel “96 FM”).

**Society and telecommunication**

Telecommunication is an important part of modern society. In 2006, estimates placed the telecommunication industry's revenue at $1.2 trillion or just under 3% of the gross world product (official exchange rate).

On the microeconomic scale, companies have used telecommunication to help build global empires. This is self-evident in the case of online retailer Amazon.com but, according to academic Edward Lenert, even the conventional retailer Wal-Mart has benefited from better telecommunication infrastructure compared to its competitors. In cities throughout the world, home owners use their telephones to organize many home services ranging from pizza deliveries to electricians. Even relatively poor communities have been noted to use telecommunication to their advantage. In Bangladesh's Narshingdi district, isolated villagers use cell phones to speak directly to wholesalers and arrange a better price for their goods. In Cote d'Ivoire, coffee growers share mobile phones to follow hourly variations in coffee prices and sell at the best price.

On the macroeconomic scale, Lars-Hendrik Röller and Leonard Waverman suggested a causal link between good telecommunication infrastructure and economic growth. Few dispute the existence of a correlation although some argue it is wrong to view the relationship as causal.

Due to the economic benefits of good telecommunication infrastructure, there is increasing worry about the digital divide. This is because the world's population does not have equal access to telecommunication systems. A 2003 survey by the International Telecommunication Union (ITU) revealed that roughly one-third of countries have less than 1 mobile subscription for every 20 people and one-third of countries have less than 1 fixed line subscription for every 20 people. In terms of Internet access, roughly half of all countries have less than 1 in 20 people with Internet access. From this information, as well as educational data, the ITU was able to compile an index that measures the overall ability of citizens to access and use information and communication technologies. Using this measure, Sweden, Denmark and Iceland received the highest ranking while the African countries Niger, Burkina Faso and Mali received the lowest.

**Digital image processing** is the use of computer algorithms to perform image processing on digital images. As a subfield of digital signal processing, digital image processing has many advantages over analog image processing; it allows a much wider range of algorithms to be applied to the input data, and can avoid problems such as the build-up of noise and signal distortion during processing.

The most common kind of digital image processing is digital image editing

## 9. Applications

### Digital camera images

Digital cameras generally include dedicated digital image processing chips to convert the raw data from the image sensor into a color-corrected image in a standard image file format. Images from digital cameras often receive further processing to improve their quality, a distinct advantage digital cameras have over film cameras. The digital image processing is typically done by special software programs that can manipulate the images in many ways.

Many digital cameras also enable viewing of histograms of images, as an aid for the photographer to better understand the rendered brightness range of each shot.

**Image processing** is any form of signal processing for which the input is an image, such as photographs or frames of video; the output of image processing can be either an image or a set of characteristics or parameters related to the image. Most image-processing techniques involve treating the image as a two-dimensional signal and applying standard signal-processing techniques to it

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Image processing usually refers to digital image processing, but optical and analog image processing are also possible. This article is about general techniques that apply to all of them.

## 10. Typical operations

The red, green, and blue color channels of a photograph by Sergei Mikhailovich Prokudin-Gorskii. The fourth image is a composite.

Among many other image processing operations are:

Geometric transformations such as enlargement, reduction, and rotation

Color corrections such as brightness and contrast adjustments, quantization, or conversion to a different color space

Digital compositing or optical compositing (combination of two or more images). Used in filmmaking to make a "matte"

Interpolation, demosaicing, and recovery of a full image from a raw image format using a Bayer filter pattern

Image editing (e.g., to increase the quality of a digital image)

Image differencing

Image registration (alignment of two or more images)

Image stabilization

Image segmentation

Extending dynamic range by combining differently exposed images

## 11. Additional Applications

Computer vision

Face detection

Feature detection

Lane departure warning system

Non-photorealistic rendering

Medical image processing

Microscope image processing

Morphological image processing

Remote sensing

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## 13. Acknowledgment

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