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Text (English)

DSPGuide - Chapter 3: ADC and DAC

Introduction

Most of the signals directly encountered in science and engineering are *continuous*: light intensity that changes with distance; voltage that varies over time; a chemical reaction rate that depends on temperature, etc. Analog-to-Digital Conversion (ADC) and Digital-to-Analog Conversion (DAC) are the processes that allow digital computers to interact with these everyday signals. Digital information is different from its continuous counterpart in two important respects: it is *sampled*, and it is *quantized*. Both of these restrict how much information a digital signal can contain. This chapter is about *information management*: understanding what information you need to retain, and what information you can afford to lose. In turn, this dictates the selection of the sampling frequency, number of bits, and type of analog filtering needed for converting between the analog and digital realms.

Quantization

First, a bit of trivia. As you know, it is a *digital* computer, not a *digit* computer. The information processed is called *digital* data, not *digit* data. Why then, is analog-to-digital conversion generally called: *digitize and digitization,* rather than *digitalize and digitalization*? The answer is nothing you would expect. When electronics got around to inventing digital techniques, the preferred names had already been snatched up by the medical community nearly a century before. *Digitalize* and *digitalization* mean to administer the heart stimulant *digitalis*.

Figure 3-1 shows the electronic waveforms of a typical analog-to-digital conversion. Figure (a) is the analog signal to be digitized. As shown by the labels on the graph, this signal is a *voltage* that varies over *time*. To make the numbers easier, we will assume that the voltage can vary from 0 to 4.095 volts, corresponding to the digital numbers between 0 and 4095 that will be produced by a 12 bit digitizer. Notice that the block diagram is broken into two sections, the sample-and-hold (S/H), and the analog-to-digital converter (ADC). As you probably learned in electronics classes, the sample-and-hold is required to keep the voltage entering the ADC constant while the conversion is taking place. However, this is *not* the reason it is shown here; breaking the digitization into these two stages is an important theoretical model for understanding digitization. The fact that it happens to look like common electronics is just a fortunate bonus.

As shown by the difference between (a) and (b), the output of the sample-and-hold is allowed to change only at periodic intervals, at which time it is made identical to the instantaneous value of the input signal. Changes in the input signal that occur between these sampling times are completely ignored. That is, **sampling** converts the *independent variable* (time in this example) from continuous to discrete.

As shown by the difference between (b) and (c), the ADC produces an integer value between 0 and 4095 for each of the flat regions in (b). This introduces an error, since each plateau can be *any* voltage between 0 and 4.095 volts. For example, both 2.56000 volts and 2.56001 volts will be converted into digital number 2560. In other words, **quantization** converts the *dependent variable* (voltage in this example) from continuous to discrete.

Notice that we carefully avoid comparing (a) and (c), as this would lump the sampling and quantization together. It is important that we analyze them separately because they degrade the signal in different ways, as well as being controlled by different parameters in the electronics. There are also cases where one is used without the other. For instance, sampling without quantization is used in switched capacitor filters.

First we will look at the effects of quantization. Any one sample in the digitized signal can have a maximum error of **±? LSB** (**Least Significant Bit**, jargon for the distance between adjacent quantization levels). Figure (d) shows the quantization error for this particular example, found by subtracting (b) from (c), with the appropriate conversions. In other words, the digital output (c), is equivalent to the continuous input (b), *plus* a quantization error (d). An important feature of this analysis is that the quantization error appears very much like *random noise*.

This sets the stage for an important model of quantization error. In most cases, *quantization results in nothing more than the addition of a specific amount of random noise to the signal*. The additive noise is uniformly distributed between ±? LSB, has a mean of zero, and a standard deviation of 1/√12 LSB (~0.29 LSB). For example, passing an analog signal through an 8 bit digitizer adds an rms noise of: 0.29/256, or about 1/900 of the full scale value. A 12 bit conversion adds a noise of: 0.29/4096 ≈ 1/14,000, while a 16 bit conversion adds: 0.29/65536 ≈ 1/227,000. Since quantization error is a random noise, the *number of bits* determines the *precision* of the data. For example, you might make the statement: "We increased the precision of the measurement from 8 to 12 bits."

This model is extremely powerful, because the random noise generated by quantization will simply add to whatever noise is already present in the analog signal.

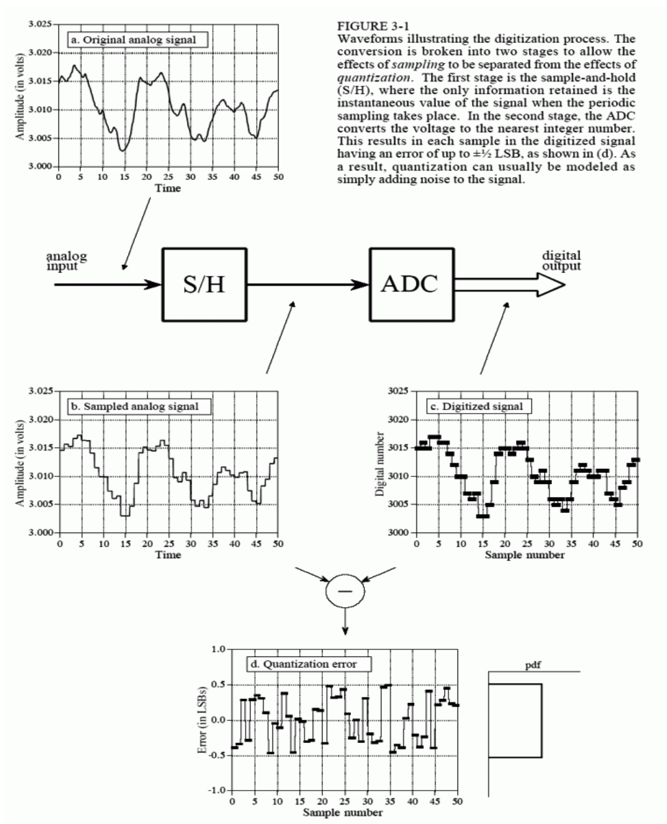

FIGURE 3-1
Waveforms illustrating the digitization process. The conversion is broken into two stages to allow the effects of *sampling* to be separated from the effects of *quantization*. The first stage is the sample-and-hold (S/H), where the only information retained is the instantaneous value of the signal when the periodic sampling takes place. In the second stage, the ADC converts the voltage to the nearest integer number. This results in each sample in the digitized signal having an error of up to ±½ LSB, as shown in (d). As a result, quantization can usually be modeled as simply adding noise to the signal.

For example, imagine an analog signal with a maximum amplitude of 1.0 volts, and a random noise of 1.0 millivolts rms. Digitizing this signal to 8 bits results in 1.0 volts becoming digital number 255, and 1.0 millivolts becoming 0.255 LSB. As discussed in the last chapter, random noise signals are combined by adding their *variances*. That is, the signals are added in quadrature: $\sqrt{(A^2 + B^2)} = C$. The total noise on the digitized signal is therefore given by: $\sqrt{(0.255^2 + 0.29^2)} = 0.386$ LSB. This is an increase of about 50% over the noise already in the analog signal. Digitizing this same signal to 12 bits would produce virtually no increase in the noise, and *nothing* would be lost due to quantization. When faced with the decision of how many bits are needed in a system, ask two questions: (1) How much noise is *already* present in the analog signal? (2) How much noise can be *tolerated* in the digital signal?

When isn't this model of quantization valid? Only when the quantization error cannot be treated as random. The only common occurrence of this is when the analog signal remains at about the same value for many consecutive samples, as is illustrated in Fig. 3-2a. The output remains *stuck* on the same digital number for many samples in a row, even though the analog signal may be changing up to +? LSB. Instead of being an additive random noise, the quantization error now looks like a thresholding effect or weird distortion.

Dithering is a common technique for improving the digitization of these slowly varying signals. As shown in Fig. 3-2b, a small amount of random noise is added to the analog signal. In this example, the added noise is normally distributed with a standard deviation of 2/3 LSB, resulting in a peak-to-peak amplitude of about 3 LSB. Figure (c) shows how the addition of this dithering noise has affected the digitized signal. Even when the original analog signal is changing by less than ±? LSB, the added noise causes the digital output to randomly toggle between adjacent levels.

To understand how this improves the situation, imagine that the input signal is a constant analog voltage of 3.0001 volts, making it one-tenth of the way between the digital levels 3000 and 3001. Without dithering, taking 10,000 samples of this signal would produce 10,000 identical numbers, all having the value of 3000. Next, repeat the thought experiment with a small amount of dithering noise added. The 10,000 values will now oscillate between two (or more) levels, with about 90% having a value of 3000, and 10% having a value of 3001. Taking the average of all 10,000 values results in something close to 3000.1. Even though a single measurement has the inherent ±? LSB limitation, the statistics of a large number of the samples can do much better. This is quite a strange situation: *adding noise provides more information*.

Circuits for dithering can be quite sophisticated, such as using a computer to generate random numbers, and then passing them through a DAC to produce the added noise. After digitization, the computer can *subtract the random numbers from the digital signal using floating point arithmetic.*

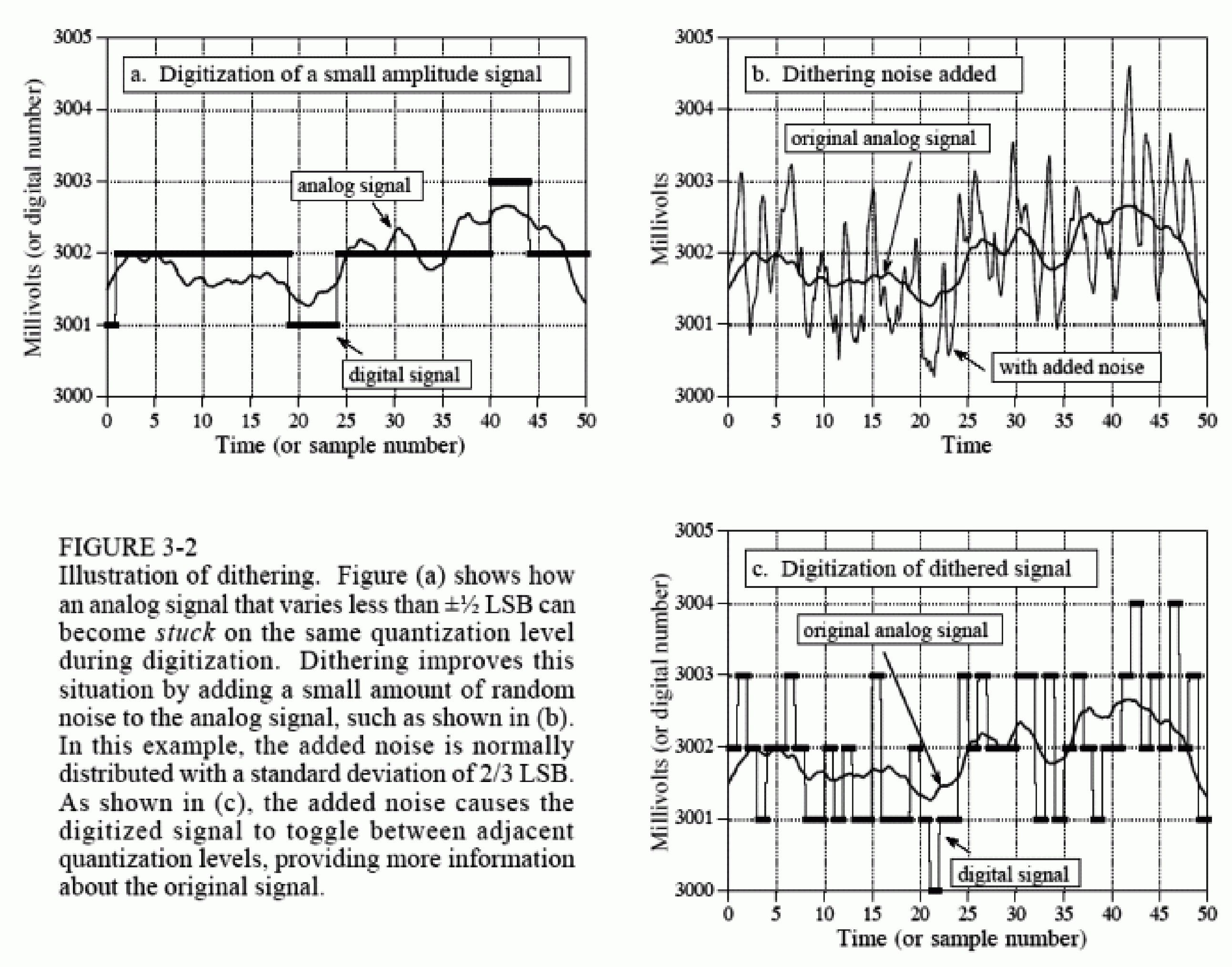

FIGURE 3-2
Illustration of dithering. Figure (a) shows how an analog signal that varies less than ±½ LSB can become *stuck* on the same quantization level during digitization. Dithering improves this situation by adding a small amount of random noise to the analog signal, such as shown in (b). In this example, the added noise is normally distributed with a standard deviation of 2/3 LSB. As shown in (c), the added noise causes the digitized signal to toggle between adjacent quantization levels, providing more information about the original signal.

This elegant technique is called **subtractive dither**, but is only used in the most elaborate systems. The simplest method, although not always possible, is to use the noise already present in the analog signal for dithering.

Text (Spanish)

DSPGuide - Capítulo 3: ADC y DAC

Introducción

La mayoría de las señales que se encuentran directamente en la ciencia y la ingeniería son continuas:

Intensidad de la luz que cambia con la distancia, voltaje que cambia con el tiempo, una reacción química que depende de la temperatura, etc. Una conversión analógico-digital (Analog-to-Digital Conversión, ADC) y una conversión digital-analógica (Digital-to-Analog Conversión, DAC) son procesos que permiten a los ordenadores digitales interactuar con las señales que nos encontramos a diario. La información digital es diferente de su homóloga señal continua en dos aspectos muy importantes: Está muestreada, y con calidad. Ambas determinan cuánta información podrá obtener una señal digital. Este capítulo tratará sobre el tratamiento de la información: entendiendo qué información se necesitará retener, y qué información se podrá perder. Sucesivamente, esto dicta la elección de la frecuencia de muestreo, número de bits y el tipo de filtro analógico que se necesitará para convertir entre lo analógico y lo digital.

Cuantificación

Primero un poco de Trivial. Como ya conoces es una calculadora digital, no una computadora de dígitos. La información procesada se llaman datos digitales, no dígitos digitales. ¿Por qué entonces, se la llama generalmente una conversión de analógico a digital en vez de llamarse digitalizar y digitalización? La respuesta no es algo que te esperarías. Cuando se empezó a inventar electrónica, los mejores nombres ya estaban cogidos por la comunidad médica desde hacía casi un siglo. Digitalizar y digitalización significa administrar los estímulos digitalis del corazón.

La figura 3-1 muestra ondas electrónicas de una conversión analógica-digital. La Figura (a) es la señal analógica que va a ser digitalizada. Como se muestra en las etiquetas del gráfico, esta señal es una tensión que varía con el tiempo. Para utilizar números más sencillos, asumiremos que la tensión variará entre 0 y 4.095 voltios, correspondientes a los números digitales entre 0 y 4095 que se producen en un proceso digital de 12 bits. Obsérvese que el diagrama de bloques está dividido en dos secciones, el sample-and-hold (S/H ó S&H), y el convertidor analógico-digital (ADC). Como probablemente hayas aprendido en clases de electrónica, el sample-and-hold se necesita para mantener la tensión guardar la tensión en la entrada del ADC mientras se lleva a cabo la conversión. Sin embargo, esta no es la razón por la que se muestra aquí; al dividir la digitalización en estas dos etapas es un modelo teórico importante para entender la digitalización. El hecho de que resulta parecido a la electrónica común es un añadido por casualidad.

Como se muestra en la diferencia entre (a) y (b), la salida del sample-and-hold sólo puede hacerse a intervalos periódicos y en este caso se hace idéntica al valor instantáneo de la señal de entrada. Se ignoran por completo los cambios que puedan suceder en la señal de entrada entre los tiempos de muestreado. Es decir, el muestreo convierte la variable independiente (el Tiempo en este ejemplo) de una señal continua a una discreta.

Las diferencias que se muestran entre las figuras (b) y (c), el conversor ADC produce un número entero entre 0 y 4095 por cada una de las regiones planas en (b). Esto introduce un error, ya que cada región plana puede ser una tensión entre 0 y 4,095 voltios. Por ejemplo, 2,56000 y 2,56001 voltios se convertirán en el mismo número digital, el 2560. Es decir, la cuantificación convierte la variable dependiente (el voltaje en este ejemplo) de una señal continua a una señal discreta.

Fíjese que estamos evitando comparar (a) y (c), como si esto amontonaría el muestreado y la cuantificación. Es importante que los analicemos por separado porque pueden degradar la señal de diferentes maneras, así como ser controlados por diferentes parámetros en la electrónica. También hay casos en los que se puede utilizar sólo uno, sin precisar para ello del otro. Por ejemplo, el muestreando sin cuantificación se utiliza en filtros interruptores de condensadores.

Primero miraremos los efectos de la cuantificación. ¿Alguna muestra la señal digitalizada puede tener un error máximo de ± el LSB? (LSB = Least Significant Bit, Bit Menos Significativo, nombre usado para la distancia entre dos niveles adyacentes de cuantificación). La figura (d) muestra el error de cuantificación de este ejemplo, que se halló tras restar (b) de (c), con las conversiones apropiadas. Es decir, la salida digital (c), es equivalente a la entrada continua (b) más un error de cuantificación (d). Una importante característica de este análisis es que el error de cuantificación se parece mucho como ruido aleatorio.

Esto fija la etapa para un modelo importante de cuantificación. En la mayoría de las ocasiones, la cuantificación da nada más que para añadir ruido aleatorio a la señal. ¿Se distribuye este ruido aleatorio de forma uniforme alrededor del ±? LSB (el Bit Menos Significativo), que es prácticamente insignificante, y una desviación estándar de 1/v12 LSB (aprox. el 0.29 LSB). Por ejemplo, una conversión de 8 bits añade un ruido medio (RMS) de 0.29/256, o sobre un 1/900 de la escala total. Una conversión de 12 bits añade un ruido de 0.29/4096 ó 1/14000, mientras que una conversión de 16 bits hace lo propio con 0.29/65536 ó 1/227000. Debido a que el error de cuantificación es un ruido aleatorio, el número de bits que determina la precisión de los bits que contengan los datos. Por ejemplo, se puede hacer la siguiente declaración. "Se incrementa la precisión de la medida desde los 8 hasta los 12 bits".

Este modelo es de gran alcance, pues el ruido aleatorio generado por la cuantificacion se añadirá a cualquier ruido que ya esté presente en la señal analógica. Por ejemplo imagina una señal analógica con una amplitud máxima de 1 voltio, y un ruido aleatorio de 1 milivoltio rms. Al digitalizar esta señal con 8 bits correspondiendo 1 voltio al número 255, y 1 milivoltio se convierte en 0.125 bits.

Glossary

Engineering (2) [Ingeniería] the discipline dealing with the art or science of applying scientific knowledge to practical problems.

Rate (3) [Velocidad] the relative speed of progress or change.

Interact (5) [Relacionarse] act together or towards others or with others.

Everyday (6) [Todos los días] suited for everyday use.

Counterpart (6) [Homólogo] a person or thing having the same function or characteristics as another.

Chapter (8) [Capítulo] a subdivision of a written work; usually numbered and titled.

Management (8) [Gestión, Tratamiento] the act of managing something.

Retain (9) [Recordar, Retener] keep in one's mind.

Afford (9) [Permitirse el lujo de] be able to spare or give up.

Lose (10) [Perder, Olvidar] fail to keep or to maintain; cease to have, either physically or in an abstract sense.

Quantization (12) [Cuantificación] is the procedure of constraining something to a discrete set of values, such as an integer, rather than a continuous set of values, such as a real number. Quantization in specific domains can take different definitions.

First (13) [Primero] before anything else.

Digitalis (18) [Digitalis] a powerful cardiac stimulant obtained from foxglove.

Figure (19) [Figura] a decorative or artistic work.

Label (20) [Etiqueta] a brief description given for purposes of identification.

Notice (23) [Obsérvese] the act of noticing or paying attention.

Keep (25) [Mantener] allow to remain in a place or position.

However (26) [Sin embargo] despite anything to the contrary (usually following a concession).

Reason (27) [Motivo] the capacity for rational thought or inference or discrimination.

Stages (27) [Nivel] a specific identifiable position in a continuum or series or especially in a process.

Fact (28) [De hecho] statement or assertion of verified information about something that is the case or has happened.

Output (30) [Salida] signal that comes out of an electronic system.

Allowed (Allow) (30) [Permitido (Permitir)] let have (grant permission).

Value (32) [Valor] a numerical quantity measured or assigned or computed.

Input (32) [Entrada] enter (data or a program) into a computer.

Flat (32) [Planicie] having a horizontal surface in which no part is higher or lower than another.

Plateau (36) [Meseta] a relatively flat highland.

Avoid (40) [Evitar] stay clear from.

Lump (40) [Agrupar, Englobar] group or chunk together in a certain order or place side by side.

Together (41) [Junto, Unido] in contact with each other.

Switched (44) [Cambiado] the act of changing one thing or position for another.

Jargon (46) [Jerga] specialized technical terminology characteristic of a particular subject.

Adjacent (47) [Contíguo] near or close to but not necessarily touching.

Feature (50) [Característica] a prominent aspect of something.

Noise (51) [Ruido] electrical or acoustic activity that can disturb communication.

Amount (53) [Cantidad] how much of something is available.

Between (54) [Entre] in the interval.

Through (55) [A través] throughout the entire extent.

Statement (59) [Declaración] a fact or assertion offered as evidence that something is true.

Measurement (60) [Medida] the act or process of measuring.

Powerful (61) [Poderoso, Potente] having the power to influence or convince.

Whatever (62) [Cualquiera] one or some or every or all without specification.

Quadrature (69) [Cuadratura] the construction of a square having the same area as some other figure.

Therefore (69) [Por tanto, Por eso] as a consequence.

Due (72) [Debido a] suitable to or expected in the circumstances.

Ask (73) [Preguntar] make a request or demand for something to somebody.

Treated (Treat) (76) [Tratado (Tratar)] subject to a process or treatment, with the aim of readying for some purpose, improving, or remedying a condition.

Occurrence (76) [Acontecimiento] an event that happens.

Row (78) [Fila] a linear array of numbers side by side.

Thresholding (80) [Umbral] the starting point for a new state or experience.

Weird (80) [Raro, Extraño] strikingly odd or unusual.

Dithering (**Dither**) (81) [Oscilante, Imprecisa, Vacilante] the process of representing intermediate colors by patterns of tiny colored dots that simulate the desired color.

Improving (Improve) (81) [Mejorando (Mejorar)] to make better.

Toggle (87) [Conmutar] a hinged switch that can assume either of two positions.

Next (91) [Después, Luego] at the time or occasion immediately following.

Thought (91) [Pensamiento (imaginado)] the process of thinking (especially thinking carefully).

Average (94) [Media (aritmética)] a statistic describing the location of a distribution.

Even though (94) [Aunque]

Inherent (95) [Inherente] in the nature of something though not readily apparent.

Strange (96) [Extraña] not at ease or comfortable.

Quite (98) [Bastante] to the greatest extent; completely.

References

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