Keywords: ecg, ekg, aed, patient monitor, diagnostic, medical equipment, electrical components, block diagram, electrocardiograph, defibrillator

TUTORIAL 4693

Introduction to Electrocardiographs

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Abstract: This application note provides an introduction to electrocardiographs (ECG or EKG) and discusses the basics of how heart signals are measured and displayed electronically. A broader review is given to the analog front-end (AFE) portion of an ECG device and how this signal path digitizes heart rate data. A variety of ECG applications are discussed, including automatic external defibrillators (AEDs), patient monitors, and higher end diagnostic ECGs, as well as the functional variations they may offer.

Overview

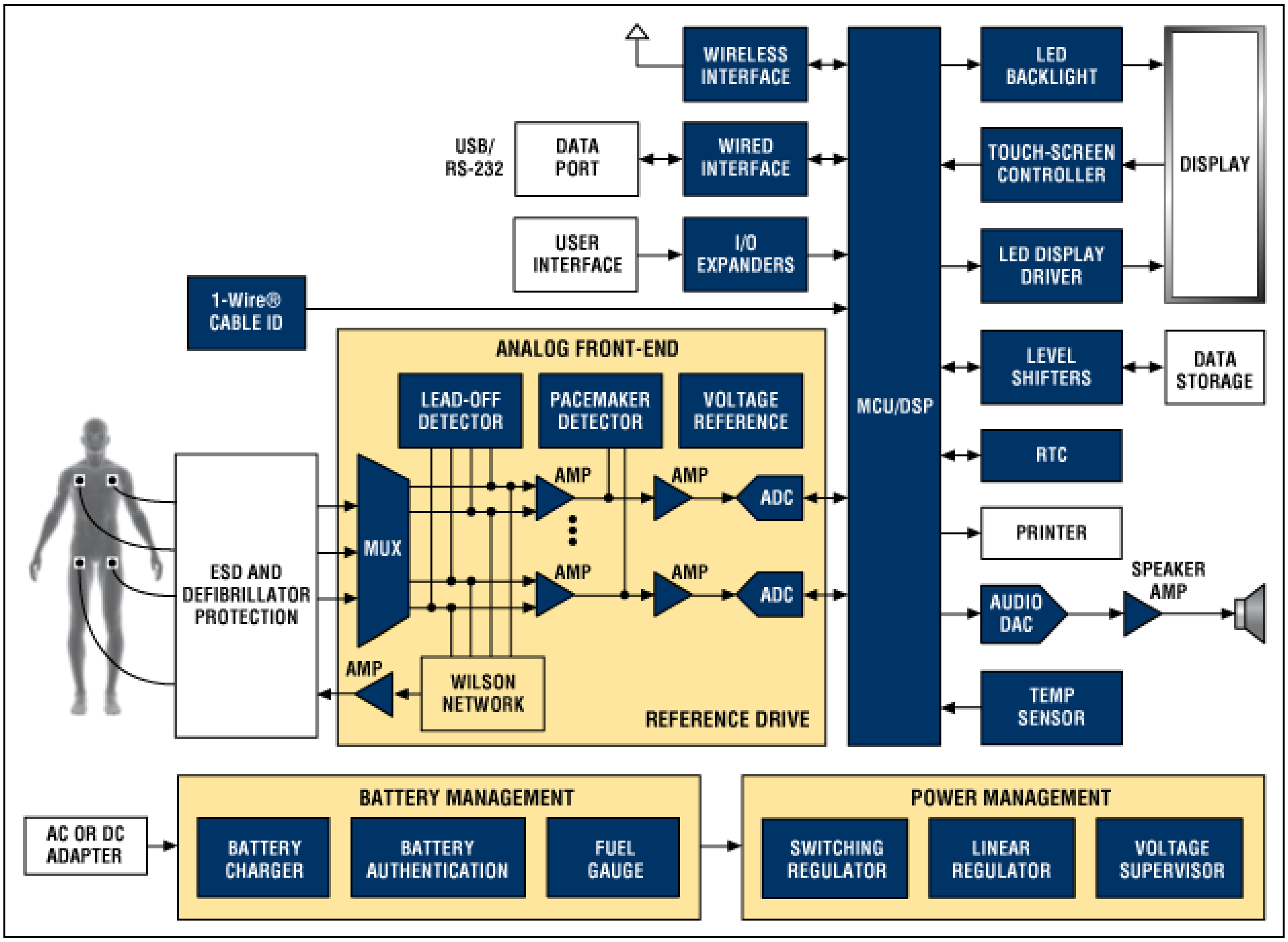
An electrocardiogram (ECG or EKG) is the measurement and graphic representation, with respect to time, of the electrical signals associated with the heart muscles. Applications of an ECG range from monitoring heart rate to the diagnosis of specific heart conditions. The basics of ECG measurement are the same for all applications, but the details and requirements for electrical components vary greatly. Electrocardiographs, or ECG devices, range from portable handheld units costing less than $200, to units that cost over $5,000 and are the size of facsimile machines. An ECG may even be embedded in a separate piece of equipment, such as a patient monitor or an automatic external defibrillator (AED).

All ECGs pick up heart signals through electrodes connected externally to specific locations on the body. The heart signals are generated by the body and have amplitudes of a few millivolts. The specific locations of the electrodes allow the heart's electrical activity to be viewed from different angles, each of which is displayed as a channel on the ECG printout. Each channel represents the differential voltage between two of the electrodes, or the differential voltage between one electrode and the average voltage from several electrodes. The different combinations of electrodes allow more channels to be displayed than there are electrodes. The channels are commonly referred to as "leads," so a 12-lead ECG device has 12 separate channels displayed graphically. The number of leads varies from 1 to 12 depending on the application. Unfortunately, the wires running to the electrodes are occasionally referred to as leads as well. This can create confusion, as a 12-lead (12-channel) ECG device only requires 10 electrodes (10 wires), so be careful of the context in which "lead" is used.

Patient monitor showing ECG and pulse oximetry readings.

In addition to the biological signals, most ECGs also detect two manmade signals. The most important of these signals comes from implanted pacemakers and is referred to simply as "pace." The pace signal is relatively short, tens of microseconds to a couple of milliseconds, with an amplitude ranging from a few millivolts to nearly a volt. Often, the ECG must detect the presence of a pace signal while simultaneously preventing it from distorting the signals from the heart.

The second manmade signal is for detecting "lead-off," which is when an electrode is making poor electrical contact. Many ECG devices must provide an alert when this poor contact occurs. Therefore, the ECG device generates a signal to measure the impedance between the electrode and the body for detecting a lead-off occurrence. The measurement may be AC, DC, or both. In some ECG devices, respiration rate is also detected by analyzing the impedance from the lead-off measurement. Lead-off detection is continuous and should not interfere with accurate measurement of the heart signals.



Full-featured ECG functional block diagram. For a list of Maxim's recommended solutions for an ECG design, please go to: www.maximintegrated.com/ECG.

Features

Understanding the required electronic components for an ECG is easier if it is separated into the analog front-end (AFE), which digitizes these signals, and "the rest of the system," which analyzes, displays, stores and transmits the data. AFEs share the same basic requirements, but differ in the number of leads, fidelity of signal, interference that must be rejected, and so on. The rest of the system differs more radically according to whether features are or are not present. Typical features include a built-in display, the ability to print a hard copy, a radio-frequency (RF) link, and rechargeable batteries.

Number of Leads

One of the most obvious features is the number of leads. Some ECGs have only one lead; the maximum number of leads is usually 12. The most common 12-lead ECGs require 10 electrodes. Nine of the electrodes pick up electrical signals and the tenth electrode, on the right leg (RL), is electrically driven by the ECG circuit to reduce the common-mode voltage. The nine input electrodes are: left arm (LA), right arm (RA), left leg (LL), and six precordial (chest) electrodes (V1 through V6). Each lead, or view of the heart, is the differential voltage between one electrode and another electrode or group of electrodes. When electrodes are grouped, their voltage is averaged. RA, LA, and LL are averaged for six of the leads (views) and become one side of the differential pair, while V1 to V6 are individually used for the other side of the differential pair. Three of the leads measure RA, LA, and LL against the average of the other two electrodes. The remaining three leads come from RA, LA, and LL measured as individual pairs. The six leads based on RA, LA, and LL contain duplicate information, but display it in different ways. Because the information is redundant, it is not necessary to measure all six leads. Some of the channels can be calculated by a DSP as it analyzes data from the measured channels.

While the 12-lead system described here is the most common, it is not the only one. In addition, 12-lead ECGs are capable of operating as a 5-, 3-, or 1-lead systems. The key point here is the need for a switch matrix and averaging circuits when more than one lead is required.

Analog Front-End (AFE)

The primary function of the AFE is to digitize the heart signals. This process is complicated by the need to reject interference from strong RF sources, pace signals, lead-off signals, common-mode line frequency, signals from other muscles, and electrical noise. In addition, the millivolt-level ECG signal can be sitting atop a DC offset that is hundreds of millivolts, with channel-to-channel common-mode voltages differing by over a volt. The electrical connections to the patient must not create a shock hazard or interfere with other medical equipment that may be connected to the patient. The frequency range of interest for the ECG varies somewhat with the application, but is usually around 0.05Hz to 100Hz.

Secondary functions of the AFE are the detection of pace signals, lead-off detections, respiration rate, and patient impedance. All of this is done on several channels simultaneously or near simultaneously. In addition, most ECG devices are required to recover quickly from a defibrillation event, which can saturate the front-end and charge capacitors. This creates a long recovery time for capacitively coupled circuits.

AFE Capabilities of Various ECG Applications

Capabilities	Patient Monitor	Diagnostic	Telemetry	Holter	AED	Consumer
High RF immunity	U	U	S	S	S	N
Minimum frequency (Hz)	0.05	0.05	0.1	0.1	0.5	0.5
Maximum frequency (Hz)	500	500	50	150	40	40
ADC sample rate (sps)	1k to 100k	1k to 100k	1024	1024	250+	250+
ADC resolution (bits)	12 to 20	12 to 20	12 to 20	12 to 20	12	10 to 12
Right leg drive	A	A	S	S	N	S
Pace	A	A	U	U	U	S
Lead-off detection	A	A	U	U	A	S
Respiration	U	S	S	S	S	N
Impedance	S	S	S	S	U	N
Defibrillation compatible	A	U	A	U	A	S

A = always, U = usually, S = sometimes, N = never

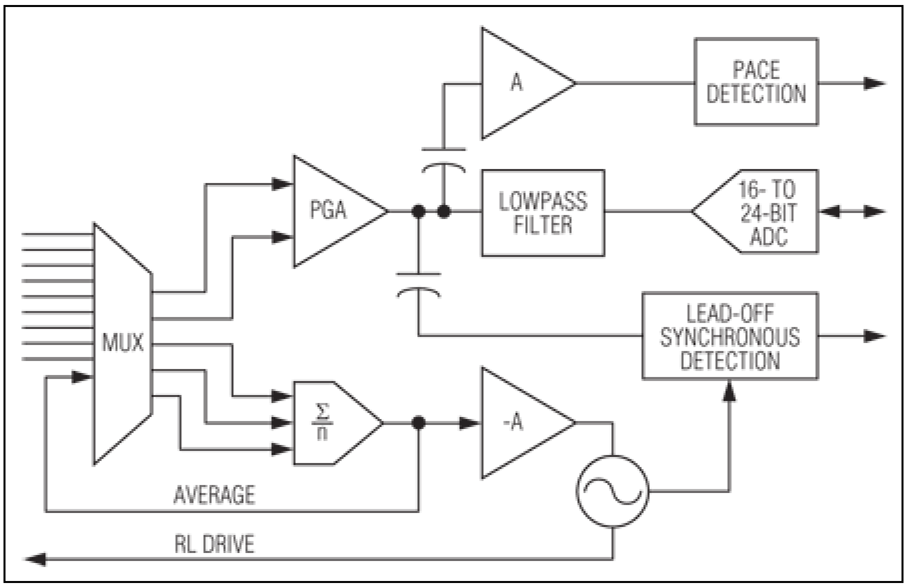
AFE Architectures

The AFE architecture has a large impact on the features. The brute force architecture described below provides high fidelity over a wide frequency range due to its high-resolution, high-conversion-rate ADC. The lack of capacitive coupling and use of a DAC for RL drive enables it to recover very quickly from a defibrillation or RF event. Digitizing the pace signal allows pace analysis that reduces the number of false pace indications and may even detect faults in the pacemaker or its connections. On the down side, the brute force system requires expensive components and uses a great deal of power. In contrast, the minimal AFE features low cost and long battery life, but little else.

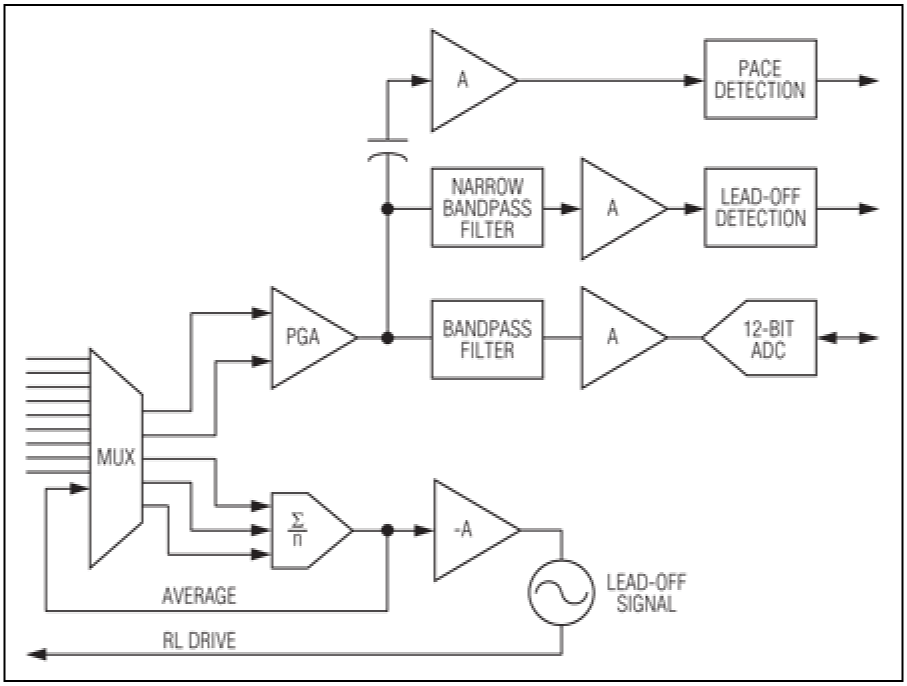
Brute force and DSP AFEs. The measurement requirements of an ECG can be met by using the brute force of powerful ADCs to simultaneously digitize the signals on all nine electrodes to a noise-free resolution of about 20 bits at a rate of 200ksps. A digital signal processor (DSP) can then be used to calculate the signal for each lead, isolate the pace signal, isolate the lead-off/respiration signals, and filter out unwanted frequencies. The DSP also calculates values for a digital-to-analog converter (DAC) driving the RL electrode. This AFE method requires the analog-to-digital (ADC) channels to be tightly matched and may require buffering to isolate the ADC sampling capacitance from the relatively high-impedance electrodes. While this approach may meet the measurement requirement, it will not meet the cost or power consumption requirements of most applications.

Minimal AFEs. At the other end of the AFE features spectrum is the 1-lead, consumer-grade ECG. The AFE circuit of this device capacitively couples the input signals to a lowpass differential amplifier that is followed by a 10-bit, 120sps ADC. Capacitively coupling the inputs eliminates DC-offset issues, and lowpass filtering removes the pace signal. There is no common-mode voltage, because the device is battery powered and has only one channel.

Typical ECG AFEs. The circuits in most ECG devices lie between the above two extremes. Instrumentation amplifiers (IAs) are used to reduce the common-mode voltage, eliminate common-mode noise such as line frequency, and provide a buffer for the ADC's sampling capacitance. Filters after the IA remove the pace and lead-off signals before the heart signals are digitized by the ADC. In some cases, the heart signal and its DC offset are directly digitized by a high-resolution ADC. In other cases, highpass filtering or DACs are used to remove the DC offset so that the heart signal can be amplified and digitized by a lower resolution ADC, typically 12 bits. A separate ADC can be used for each lead, or one ADC can be multiplexed to digitize multiple leads. Multiplexing the ADC can cause a slight time skew between channels. How objectionable this skew is depends on the application. If pace detection is needed, the pace signal is picked off by a highpass filter, amplified, and detected by a comparator circuit.



DC-coupled, high-resolution ADC



AC-coupled ADC

Types of ECG Equipment

Telemetry Devices

ECG telemetry systems are used to continuously monitor ambulatory patients in a clinical setting. They consist of an RF-equipped ECG measurement unit worn by the patient and a central RF receiving station that collects and analyzes the data from many patients. Some telemetry systems provide additional data such as blood-oxygen levels. The data is used to verify or alter the effectiveness of treatments and to warn of impending problems.

Many telemetry systems are limited to 5 leads, as full 12-lead ECGs make it difficult for patients to be ambulatory. Patients typically use the device continually for a couple of days. Disposable batteries are frequently used in these devices. Other ECGs are also capable of telemetry, but the term "ECG telemetry" refers specifically to the mobile units worn in a hospital that transmit data to a local receiving station. Key considerations for telemetry system designs are low power, low noise, and small size.

Holter Monitors

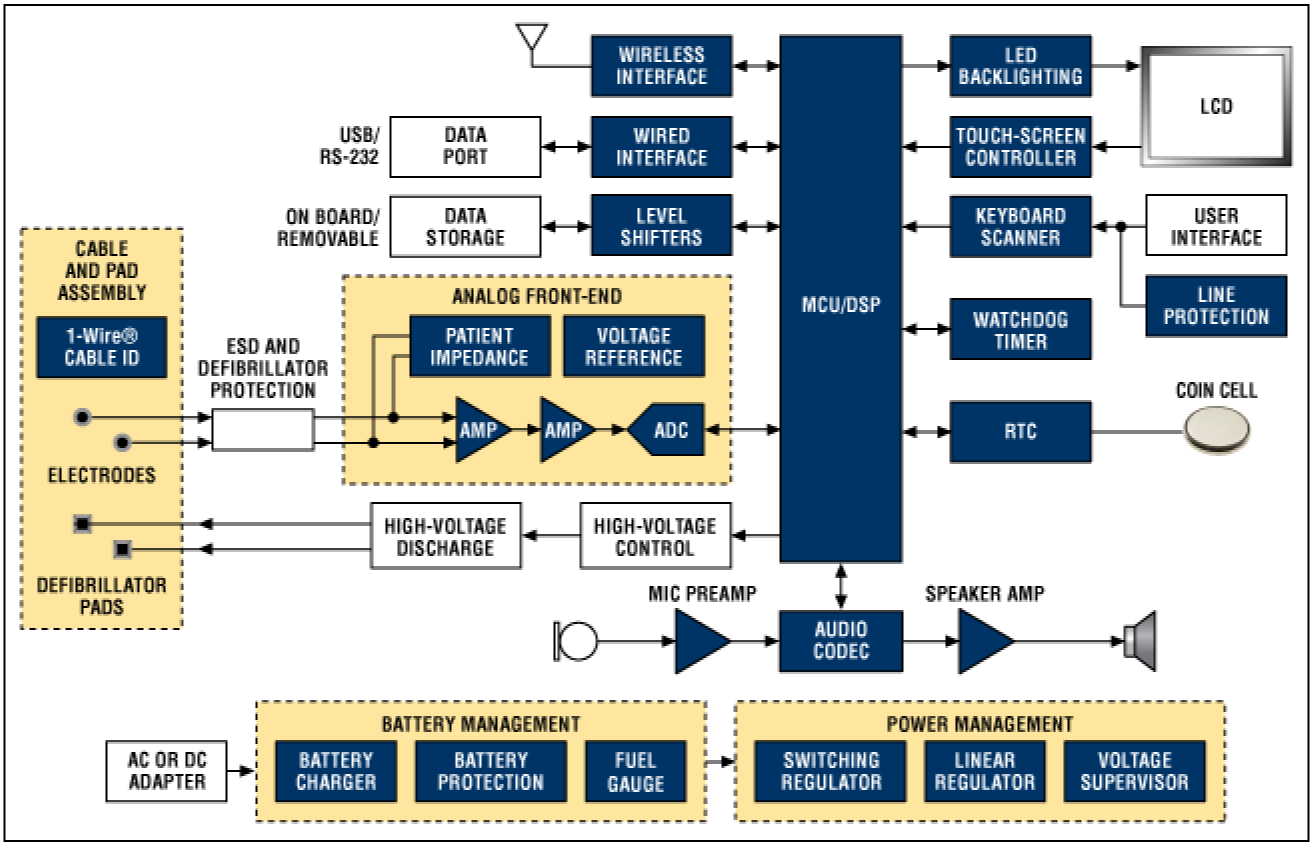
The name Holter comes from Dr. Norman Holter who invented mobile monitors for collecting data that is later uploaded to another system for analysis. Unlike a telemetry unit, these monitors do not require a central receiving station and can be used at home, outdoors, or just about anywhere. Five leads are frequently the maximum for a Holter ECG monitor, since being ambulatory is difficult with a full 12-lead ECG. Data is most commonly retrieved from the monitor by removing the memory card; however, USB and other methods are also used. Most patients need only to be monitored for a day or two. Special long-term monitors are used for patients involved in drug studies—they are used by a single patient for a year or more. Principal concerns for Holter ECG monitor designs are low power, low noise, and small size.

Consumer ECGs

These low-end ECGs easily fit in a hand and are used by people to take their own ECG test at home. The device stores the data, and also displays it on a built-in screen. This data can be transferred to a computer or sent through phone lines to a healthcare provider. Some units have multiple electrodes on wires, while others have two electrodes built into the case. Electrodes in the case can be pressed against the chest, or one hand can be placed on each electrode. The resulting ECG may not be the best quality, but it is a way for people to monitor themselves and to capture data about their heart while they are experiencing an abnormal event. Focal issues for consumer ECG designs are low cost and small size.

Automatic External Defibrillators (AEDs)

Intended for emergency use by the untrained public, these devices are frequently seen in public places such as shopping malls, gyms, and offices.



Functional block diagram for an AED device. For a list of Maxim's recommended solutions for an AED design, please go to: www.maximintegrated.com/AED.

They are used immediately after, or during, a heart attack to jump-start the heart and restore its natural rhythm by delivering a high-energy electric pulse to the chest. This pulse can also kill if delivered at the wrong time; ECG functionality is needed to ensure that this does not happen. AEDs typically have one lead and pick up the heart signal through the same pair of electrodes that deliver the high-energy pulse to the chest.

An AED could sit for months or years without use, and then be used by untrained personnel who are not likely to recognize a problem if one existed. When the system is needed, it must turn on, do a thorough self-check to verify that everything is working perfectly, and then operate for a relatively short period of time. All of the ECG data, as well as the defibrillation information, must be recorded for later analysis. Using a defective AED could do more harm than good. Therefore, reliability and self-diagnostics are essential considerations for AED designs.

Diagnostic ECGs

These machines are used in hospitals and doctors' offices to perform high-quality ECG tests. They are capable of performing a full 12-lead ECG test and creating a hard-copy printout. These units use a high-performance AFE that typically has options for gain adjustment and selection of various filters to improve the quality of the ECG measurements. Being larger and less portable, these machines have room for more features, such as built-in printers, multiple communication ports, and large display screens. These devices are line powered, but usually include a rechargeable backup battery. Key considerations for diagnostic ECG designers are low noise, interference rejection, and flexibility.

Patient Monitors

These machines monitor vital signs (pulse rate, respiration rate, blood pressure, and temperature). In addition, they may include ECG functionality, as well as monitor blood oxygen and carbon dioxide levels. Integrating all of these functions into one unit helps unclutter the operating room and simplifies the process of moving the patient from room to room without disconnecting the monitoring equipment.

The AFE used for patient monitors is similar to the AFE used in a diagnostic ECG, but must meet RF-rejection requirements—these machines are used during surgery and can receive strong RF signals from electrocautery knives and argon plasma coagulation (APC) equipment. Rapid recovery from a defibrillation event is also essential.

Patient monitors are line powered but have battery backup, which makes power consumption an important issue. The cases must be splash proof and easily cleanable. This precludes cooling vents, thereby making power dissipation a consideration. Along with power consumption and dissipation, key considerations for patient monitor designs are RF immunity and low noise.

Common Features of Various ECG Applications

Features	Telemetry	Holter	Consumer	AED	Diagnostic	Patient Monitor
Power						
Line	N	N	N	N	A	A
Rechargeable	S	S	S	S	U	A
Disposable	U	U	U	U	S	S
Communication						
RF	A	S	S	S	S	S
RS-232/RS-485	N	S	S	S	S	S
Ethernet	S	S	S	S	S	S
USB	N	S	S	S	S	S
Modem	N	S	S	S	S	S
Data card	N	U	S	S	S	S
Graphic display	S	U	A	S	S	A
Printer	N	N	N	N	A	S

A = always, U = usually, S = sometimes, N = never

Related Parts		
MAX1132	16-Bit ADC, 200ksps, 5V Single-Supply with Reference	Free Samples

MAX1162	16-Bit, +5V, 200ksps ADC with 10µA Shutdown	Free Samples
MAX1167	Multichannel, 16-Bit, 200ksps Analog-to-Digital Converters	Free Samples
MAX1300	8- and 4-Channel, ±3 x V_{REF} Multirange Inputs, Serial 16-Bit ADCs	Free Samples
MAX4194	Micropower, Single-Supply, Rail-to-Rail, Precision Instrumentation Amplifiers	Free Samples
MAX4208	Ultra-Low Offset/Drift, Precision Instrumentation Amplifiers with REF Buffer	Free Samples
MAX4238	Ultra-Low Offset/Drift, Low-Noise, Precision SOT23 Amplifiers	Free Samples
MAX9060	Ultra-Small, Low-Power Single Comparators in 4-Bump UCSP and 5-SOT23	Free Samples
MAX9617	High-Efficiency, 1.5MHz Op Amps with RRIO	Free Samples

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