Power Measurement Basics

Agilent Technologies

Back to Basics - 2005

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Slide 1

Welcome to Power Measurement Basics.

Objectives

On completion of this module, you will be able to:

- **Explain the importance of power measurements**
- **Define the three basic types of power measurements**
- **Describe the power meter/sensor measurement method**
- **Explain the two most prevalent sensor technologies**
- **Describe advanced measurements used for the latest RF & microwave applications**
- **Calculate power measurement uncertainty**
- **Outline Agilent's broad range of power measurement solutions**

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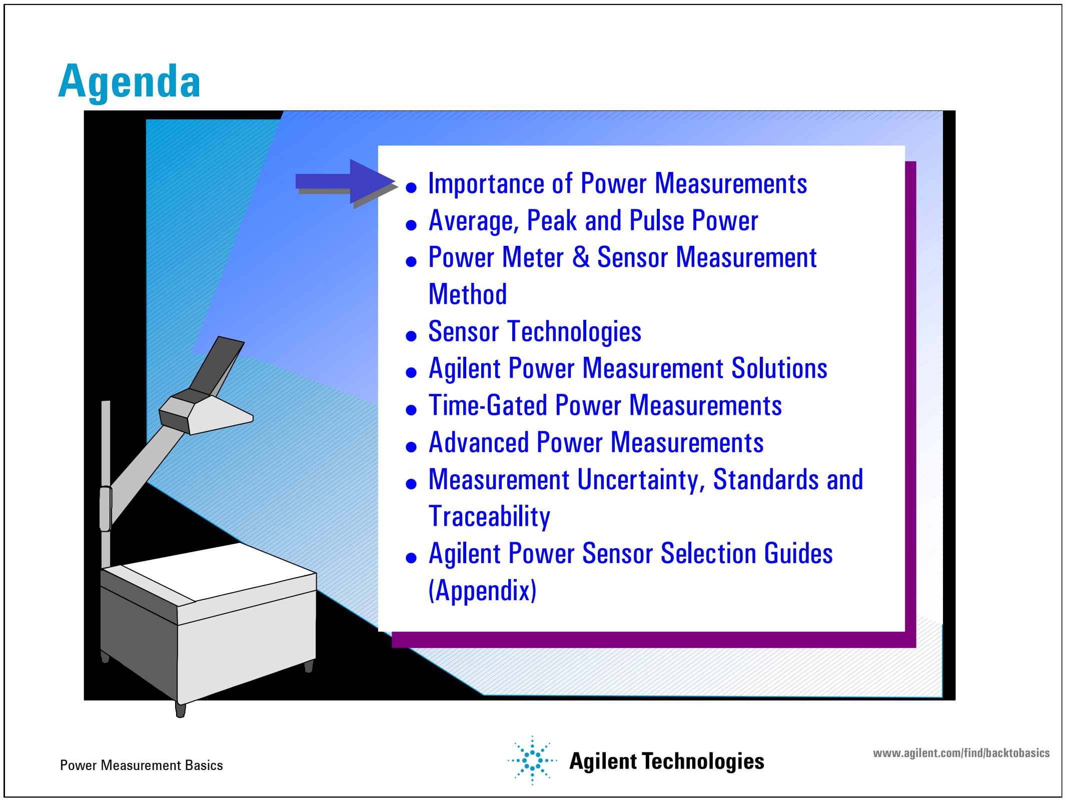
On completion of this module, you will be able to…



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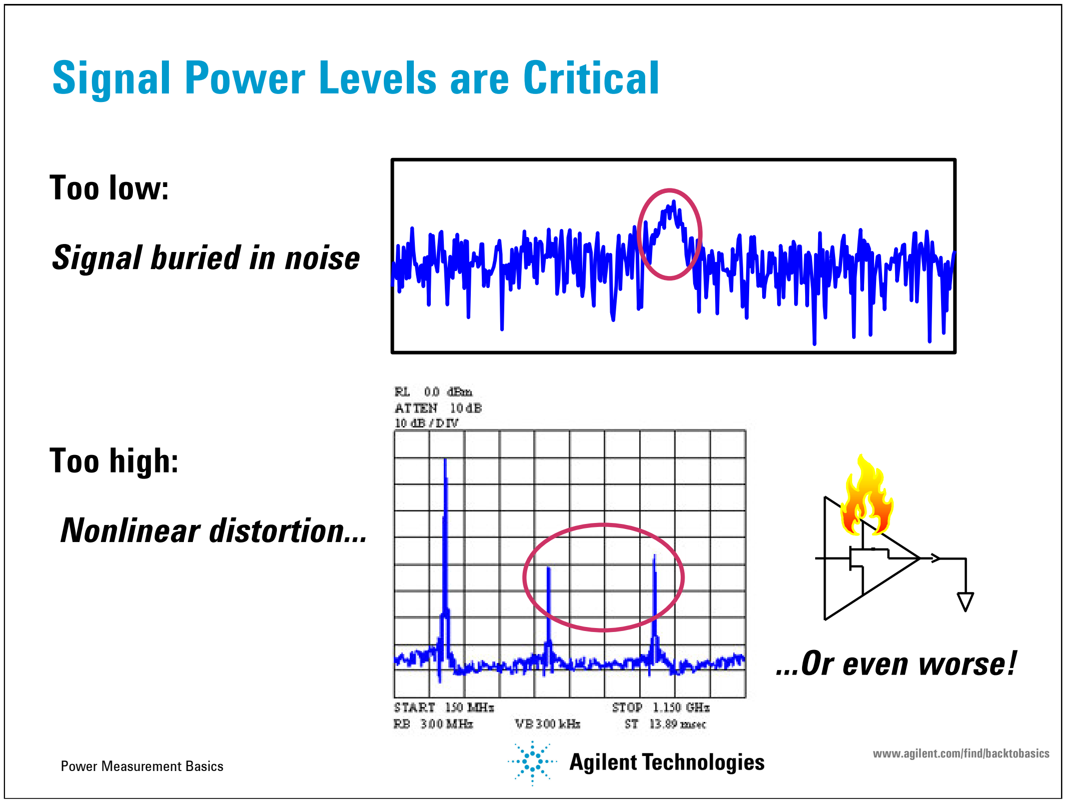
Here is a list of the major topics we'll cover. Let's begin by answering a basic question: why are power measurements important?



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The output power level of a component or system is typically the most important factor in the design and specified performance of almost all RF and microwave equipment.

In a system, each component in a signal chain must receive the proper signal level from the previous component and pass the correct signal level on to the succeeding component. If the output signal level is too low, the signal can be obscured in noise. Alternatively, if the signal level is too high, the performance will be nonlinear and distortion will result...or even worse, damage will occur.

Importance of Power Measurements

- Critical to specified performance at every level of a system
- Many measurements made in design and manufacturing
- Measuring equipment and techniques must be:
  - Accurate
  - Repeatable
  - Traceable
  - Convenient

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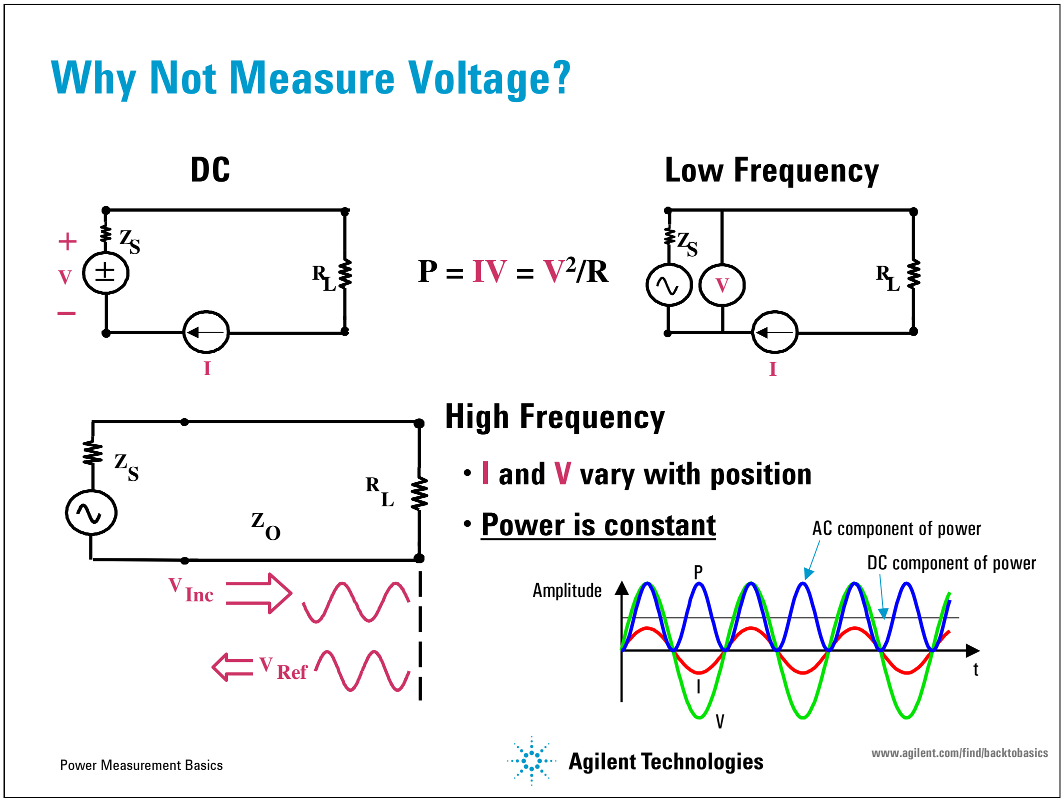
The signal power is therefore critical to performance at every level, from the most fundamental devices to the overall system. The large number of power measurements made in design and manufacturing, together with the need to replicate the measurements at different times and places, dictate that the measurement equipment and techniques be accurate, repeatable, traceable and convenient.



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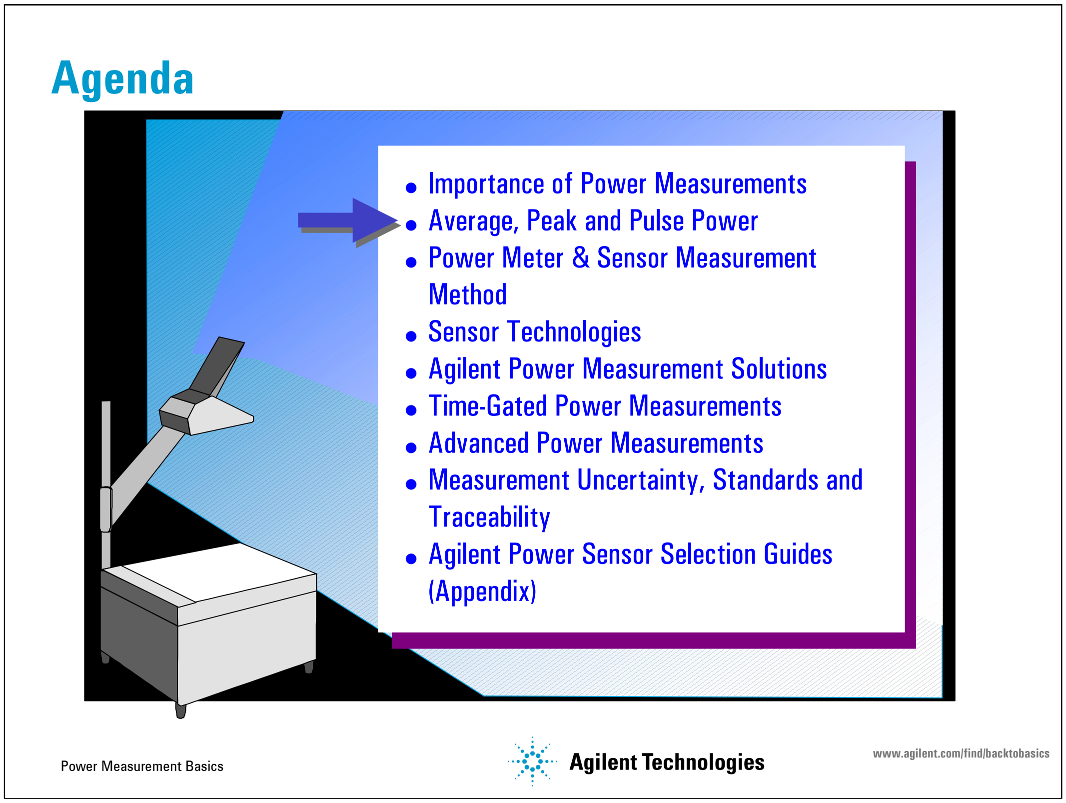
At DC and low frequencies, voltage and current measurements are simple and straightforward. If a power measurement is needed, power is easily calculated:

$$P = IV = \frac{V^2}{R} = I^2 R$$

However, as the frequency approaches 1 GHz, voltage and current measurements become difficult and impractical, and in most applications direct power measurements are made instead. One reason for this is that voltage and current may vary with position along a lossless transmission line because of standing waves produced by the interaction of incident and reflected traveling waves. However, power maintains a constant value along the transmission line. At RF and microwave frequencies, therefore, power is more easily measured, easier to understand, and more useful than voltage or current as a fundamental quantity.

Looking at the 'High Frequency' example in the slide, for maximum power transfer, the load Rl should be equal to the source output impedance Zs. In practical applications this is not achievable and some portion of the incident signal (Vinc) is reflected from the load to the source (Vrefl). When two traveling waves are present, and are traveling in opposite directions, this gives rise to so-called standing waves. The envelope of the standing wave does not change with time but remains stationary, thus the term 'standing wave'. The ratio of the maximum value (maxima) to the minimum value (minima) of the envelope is a measure of the relative amounts of oppositely traveling waves. A useful figure of merit often employed in transmission theory and practice is the 'voltage standing wave ratio' abbreviated VSWR. It is defined as the ratio of the absolute value of the maximum to the minimum value of the envelope. We will be discussing VSWR in more detail in this presentation in the Measurement Uncertainty section.



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Now, let's examine the three fundamental types of power measurements in high-frequency applications: average, peak and pulse power. First, we'll need to define "power" in RF and microwave systems.

Units and Definitions

- Power = energy transferred per unit time
- Basic power unit is the watt (W)
  - 1 W = 1 A x 1 V
- A logarithmic (decibel) scale is often used to compare two power levels
  - **Relative** power in decibels (dB) = 10 log(P_2/P_1)
- **Absolute** power is expressed by assigning a reference level to P_1
  - Power (dBm) = 10 log(P/1 mW)

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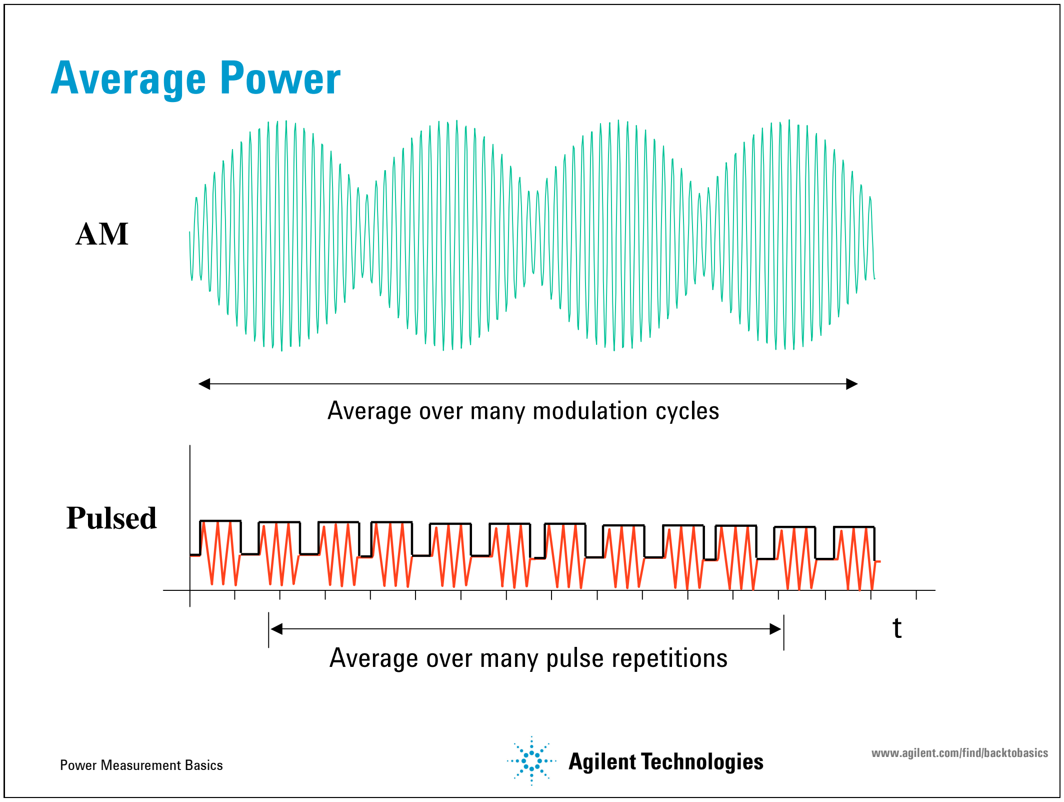
Power is defined as work done or energy transferred per unit time, and the basic unit is the watt. In electrical terms, one watt is dissipated when a current of one ampere flows across a potential difference of one volt.

We often find ourselves comparing power levels that greatly differ. For example, the output of a transmitter might be two kilowatts (2×10^3 W), while the signal level at a receiver's antenna terminal might be only five picowatts (5×10^{-12} W). Dealing with such large differences using a linear scale is awkward, so a logarithmic, or decibel scale is normally used when expressing power.

Note that the decibel, or dB is ten times the log of the *ratio* of the two power levels, P_2 and P_1; therefore, it is a relative and dimensionless unit. We can use the decibel to express *absolute* power by assigning an absolute, or reference level to P_1. At microwave frequencies, we usually assign 1 milliwatt to P_1, and describe absolute power in terms of dBm, or dB relative to 1 milliwatt.



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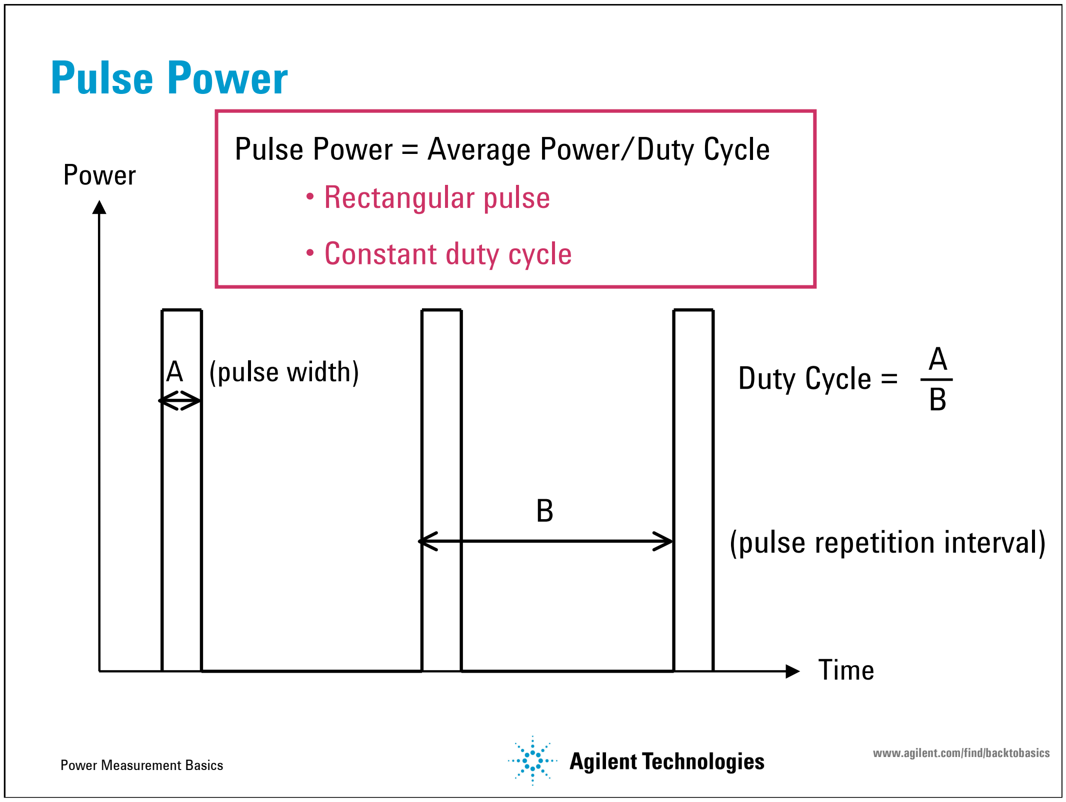
Since the instantaneous power of a modulated signal varies from one moment to the next, it is difficult to measure. Instead, a signal's *average* power is most commonly measured.

To measure average power accurately, the time constant of the sensing device must be long with respect to the lowest frequency component in the signal being measured. The power of this amplitude modulated signal [upper graph], for example, must be averaged over many cycles of the modulating signal. Similarly, the power of this pulsed signal [lower graph] must be averaged over many pulse repetitions to obtain an accurate measurement.

As we will see, test equipment for average power measurements is economical, easy to use, and most importantly accurate and traceable to national and international standards.



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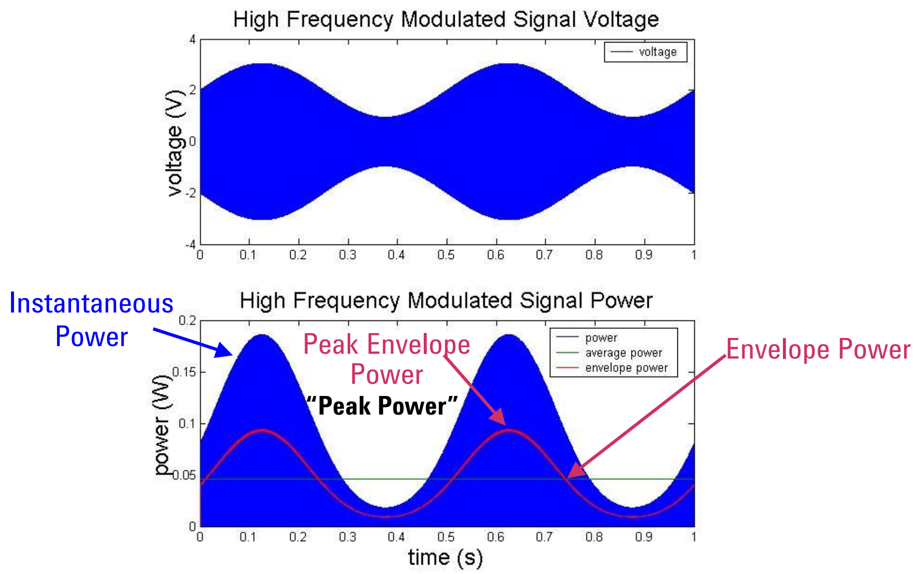
For a pulsed RF signal, such as a radar signal, the ratio of the pulse width to the pulse repetition interval is called the duty cycle. Traditionally, the power of a pulsed RF signal is determined by measuring the average power of the pulse and then dividing the result by the pulse duty cycle. The measurement result is a mathematical representation of the pulse power rather than an actual measurement and assumes constant peak power. The pulse power averages out any aberrations in the pulse, such as overshoot or ringing. For this reason it is called pulse power and not peak power or peak pulse power.

Accurate pulse power readings require that the modulating signal be a rectangular pulse with a constant duty cycle. Other pulse shapes, such as triangle or Gaussian, will cause erroneous results. This technique is not applicable for digital modulation systems, where the duty cycle is not constant, and the pulse amplitude and shape is variable.

Envelope Power and Peak Envelope Power



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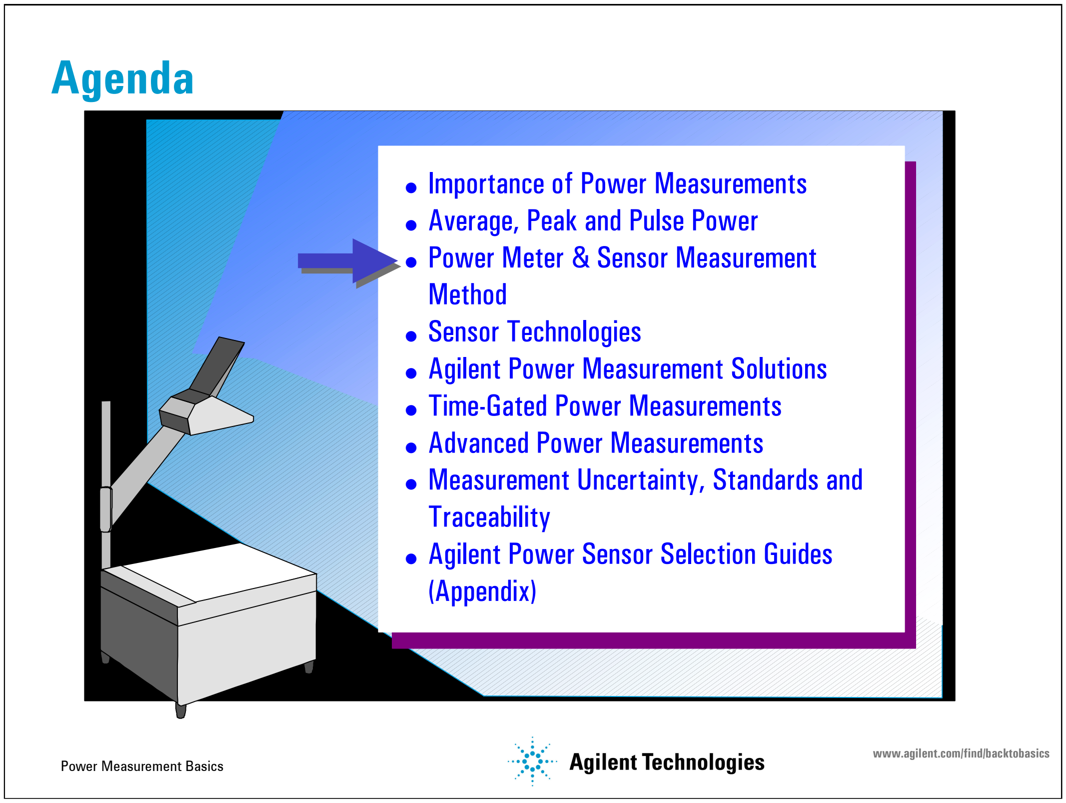
The upper graph shows the voltage envelope of a high-frequency modulated signal. The lower graph shows the instantaneous power envelope of this signal in blue, and the envelope power in red.

The envelope power is measured by averaging the power over a time period that is large compared to the period of the highest modulation frequency, but short compared to the period of the carrier. This allows engineers to examine the effects of modulation or transient conditions without examining details of the RF carrier waveform.

The peak of the envelope power is measured as peak power by a peak power meter, and is a measure of the maximum signal power.



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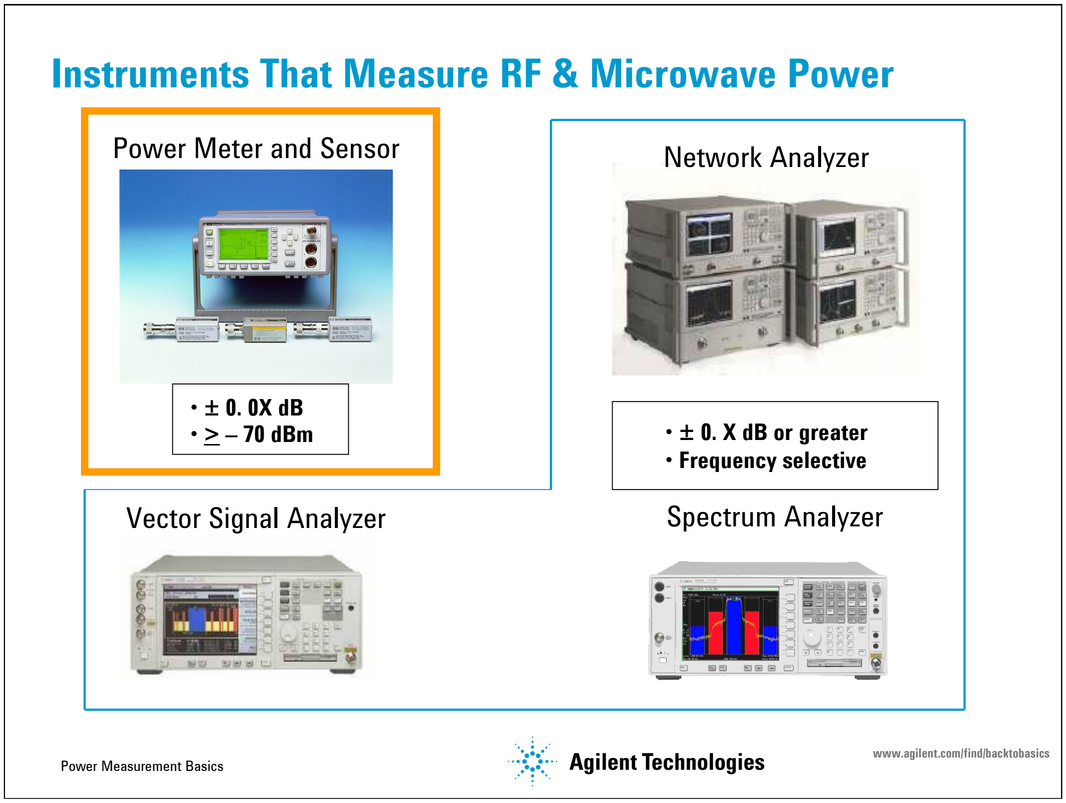
Next, we'll look at the most prevalent method for measuring power, which is using a power meter and power sensor.



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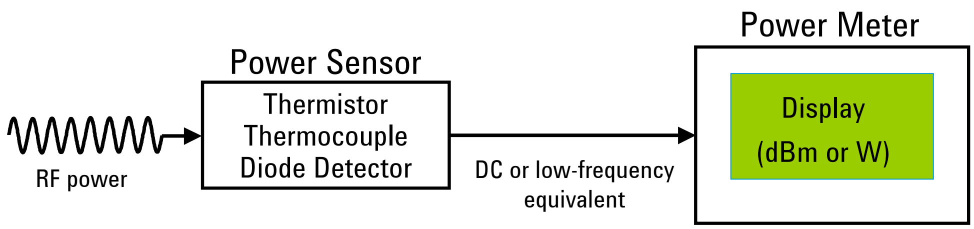
Although a variety of instruments measure RF and microwave power, including signal, spectrum and network analyzers, the most accurate is the power meter and sensor combination. Typical power meter uncertainty is on the order of hundredths of a dB, while other instruments, such as spectrum analyzers and network analyzers, have uncertainties in the tenths of a dB or greater.

One of the main differences between these instruments is frequency selectivity. A spectrum analyzer, for example, measures in a particular resolution bandwidth. The power meter is not frequency selective, since it measures the average power over the full frequency range of the sensor, and will include the power of the carrier as well as harmonics. The lack of frequency selectivity is the main reason that power sensors can only measure down to about -70 dBm. A spectrum analyzer can measure signals much lower than this when narrow resolution bandwidths are use.

The convenience, lower cost and accuracy of the power meter/sensor combination makes it the most popular method for measuring power in RF and microwave applications, and so power meters and sensors are the focus of this course.

The Power Meter and Sensor Method



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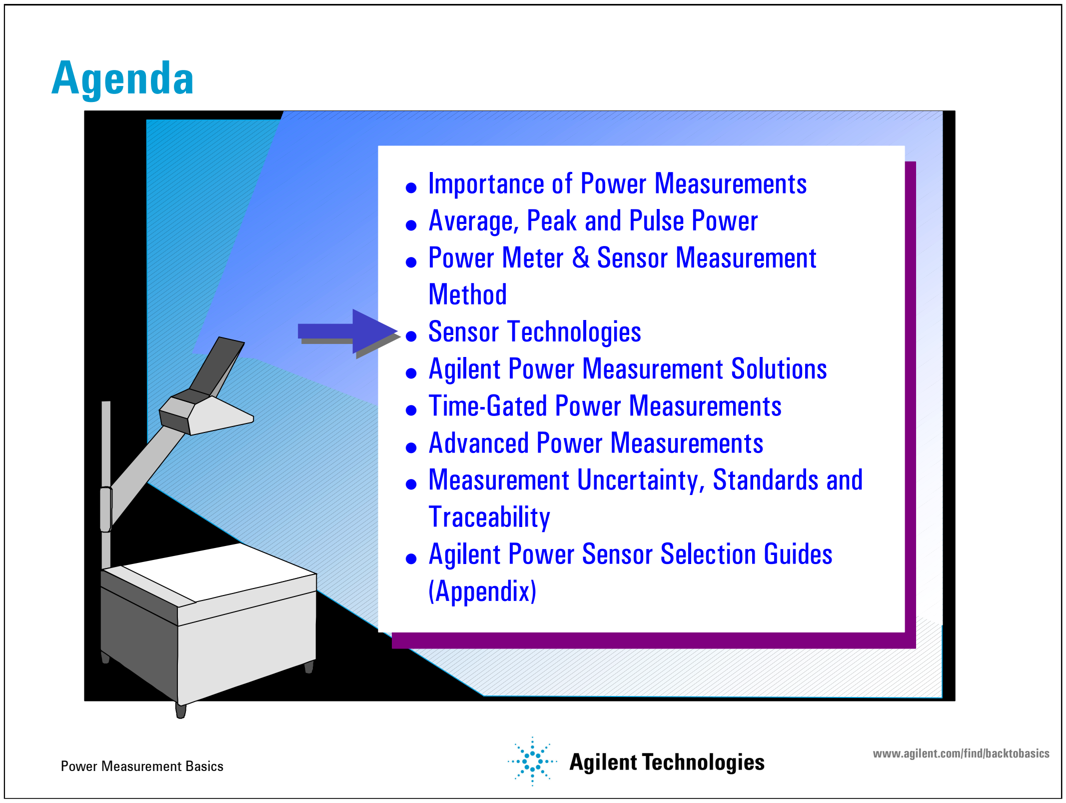
This diagram shows the basic method of measuring high-frequency power using a power meter and power sensor. The power sensor converts high-frequency power to a DC or low-frequency signal that the power meter can measure and relate to an RF power level. The meter displays the detected signal as a power value in dBm or watts.

The three main types of sensors are thermistors, thermocouples, and diode detectors. There are benefits and limitations associated with each type of sensing element.



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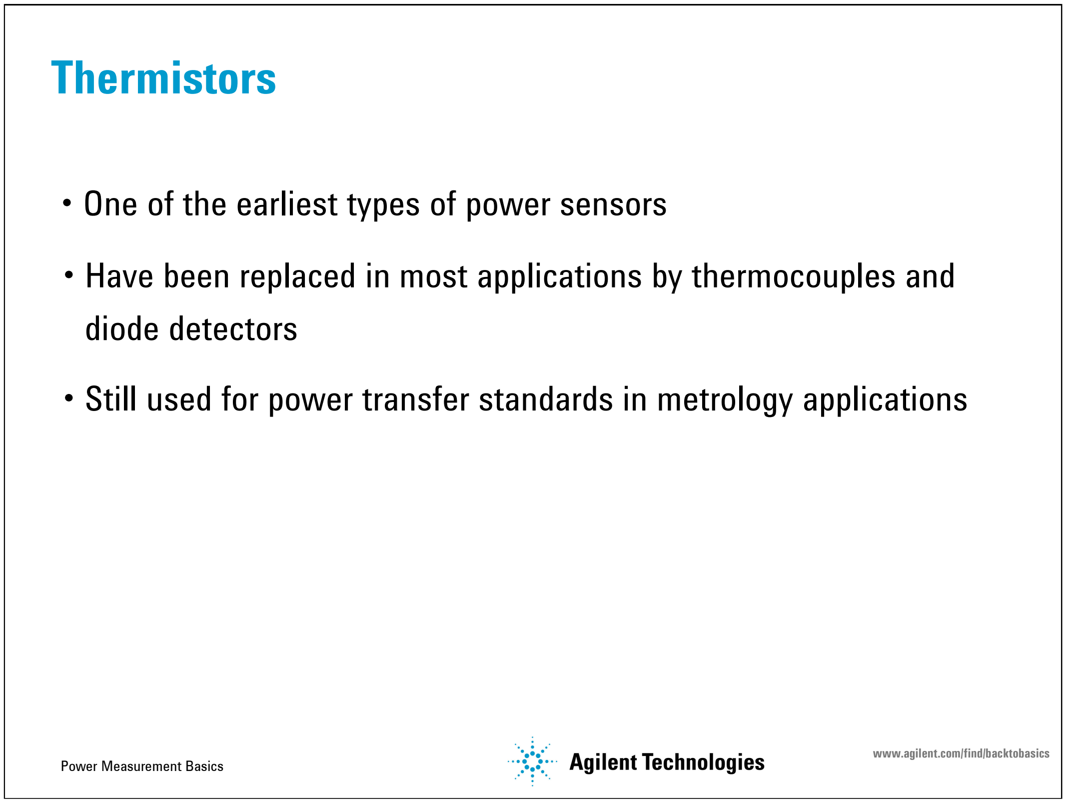
Next, we'll discuss the various technologies used in power sensors.



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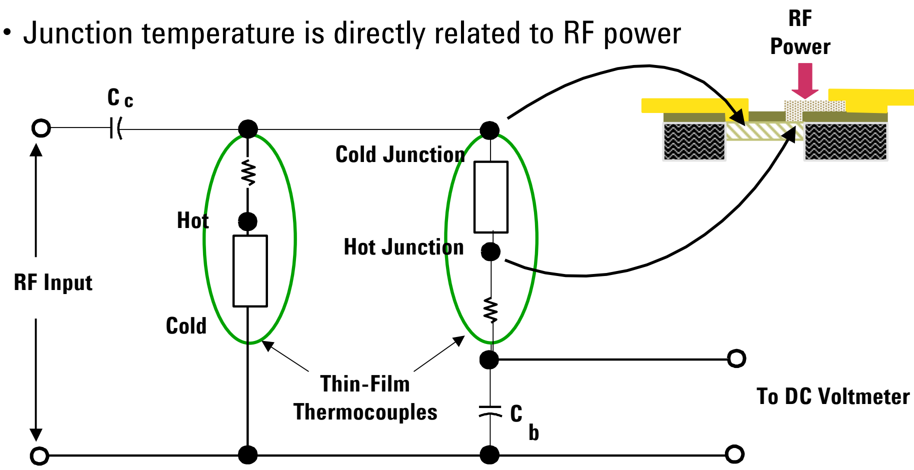
Thermistors were one of the first types of sensors used to measure RF and microwave power. However, thermocouples and diode detectors have replaced thermistors in most applications because of their greater sensitivity, wider dynamic range, and higher power capability. But thermistors are still the sensor of choice for power transfer standards in metrology applications because of their DC power substitution capability.

In this course, we will look in detail at the two most popular types of sensors, thermocouples and diode detectors.

Thermocouples

- A junction of two dissimilar metals generates a voltage related to temperature
- Junction temperature is directly related to RF power



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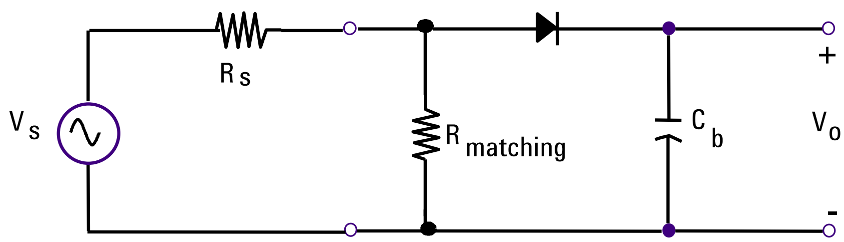
Thermocouples use the principle that the junction between two dissimilar metals generates a voltage that is a function of temperature. In a power sensor, the temperature of the junction is directly related the RF power incident on it, so the input power level can be determined from the thermocouple voltage. To make accurate measurements, a second junction that is kept at a constant temperature is used. This is called the cold junction.

One way to use thermocouple technology for a power sensor is shown in this schematic. The sensor contains two identical, thin-film thermocouples on one chip. For DC, the thermocouples are in series, while at RF frequencies they are in parallel. The two thermocouples in parallel form a 50-ohm termination for the RF transmission line.

Since thermocouples always respond to the true power of a signal, they are ideal for all types of signal formats, from CW to complex digital phase modulation formats.

Diode Detectors



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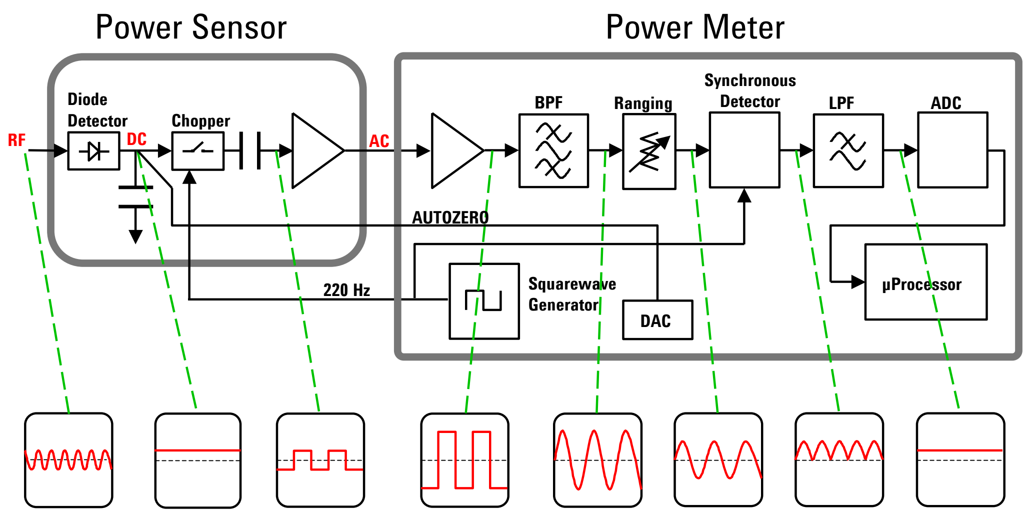
Unlike a thermocouple, a diode detector does not measure the heat content of a signal but rectifies the signal instead. The matching resistor (approximately 50 ohms) is the termination for the RF signal. The RF signal voltage (V_S) is converted to a DC voltage (V_0) at the diode, and the bypass capacitor (C_b) is a lowpass filter that removes any RF signal getting through the diode.

Power Sensor and Meter Signal Path



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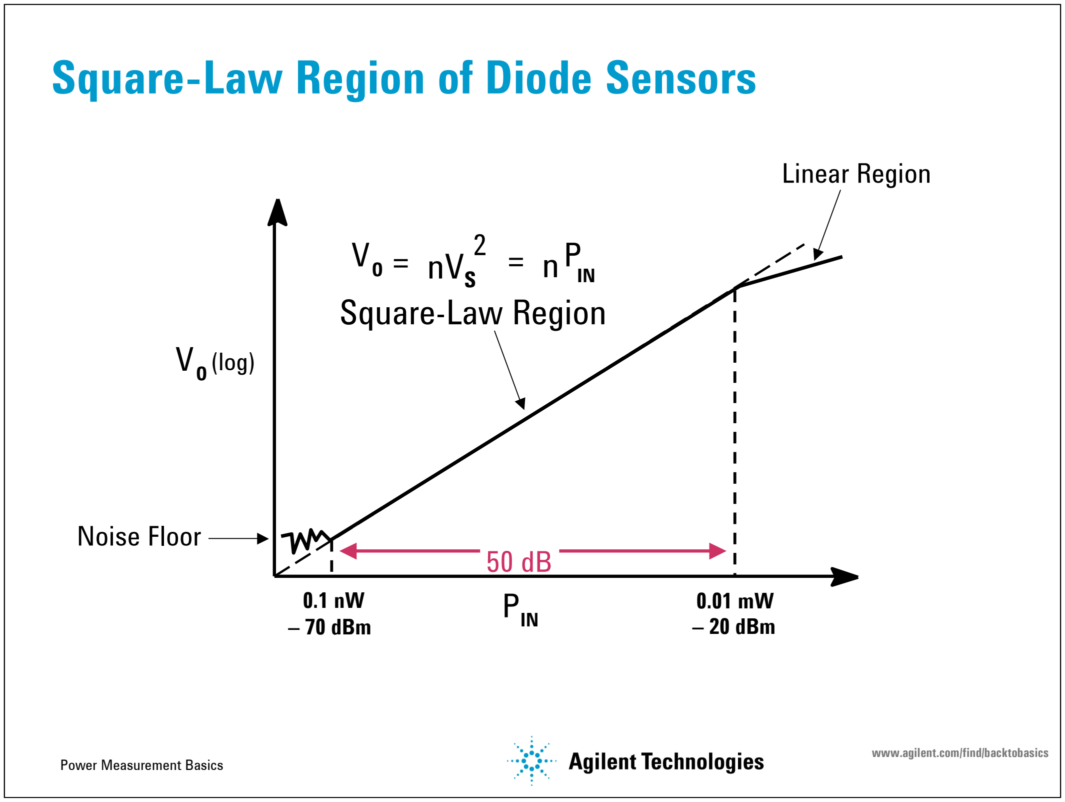
Here is a block diagram of a power sensor and meter. The incoming RF signal power causes both thermocouples and diode detectors to generate DC voltages on the order of 100 nV. Such small voltages require chopper circuits, AC amplifiers, and synchronous detectors to yield an accurate measurement of the signal under test.

Since the DC output from the detector is so small, Agilent includes the chopper and first AC amplifier in the power sensor, so that only relatively high-level signals appear on the cable connecting the sensor to the meter.

Once inside the meter, the AC signal is amplified again and passed through a bandpass filter. The narrowest bandwidth is chosen for the weakest signals and the most sensitive range. As the power meter is switched to higher ranges, the bandwidth increases so that measurements can be made more rapidly. A synchronous detector rectifies the signal, which then passes through a lowpass filter. An analog-to-digital converter takes the resulting DC signal and provides the value of the input signal power level.



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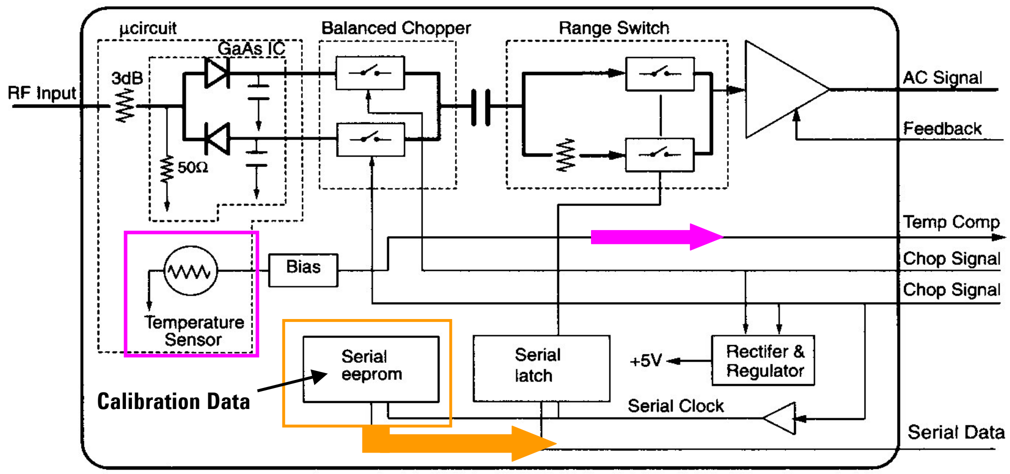
The square-law region is where the detected output voltage of a diode detector is proportional to the square of the input voltage, and therefore proportional to the input power. For diode detectors, the square-law region is approximately from – 70 to – 20 dBm, a 50 dB dynamic range. Above –20 dBm is the linear region, and correction factors must be employed to ensure accurate power measurements in this range. The stable characteristics of modern diode detectors allow data compensation and correction techniques to provide up to 90 dB of dynamic range, as we will see in the next slide.

Wide Dynamic Range CW Power Sensors

– 70 to + 20 dBm = 90 dB Dynamic Range



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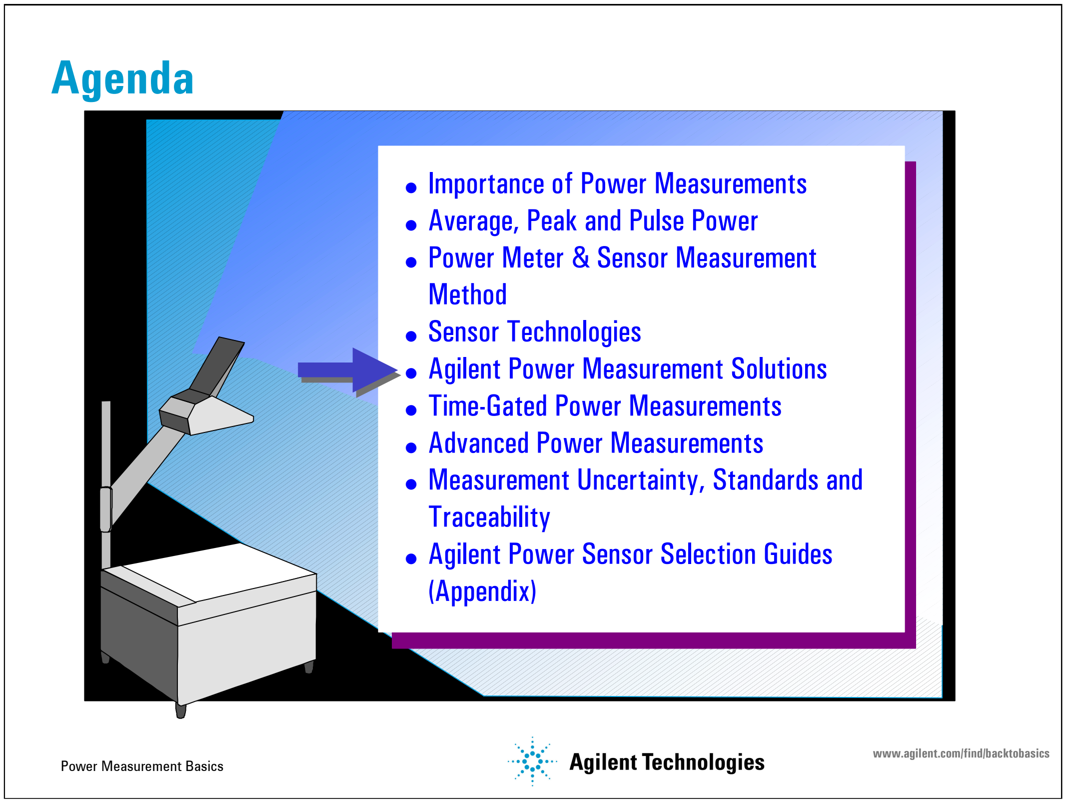
Agilent wide dynamic range CW power sensors make measurements beyond the square-law region of the diode sensing element, from – 70 to +20 dBm. To achieve this expanded dynamic range of 90 dB, the sensor/meter combination depends on calibration data stored in EEPROM in each sensor. The data consists of three parameters, input power level versus frequency versus temperature, covering the sensor’s specified ranges.

At the time of sensor power-up, the power meter uploads the sensor’s calibration data. An internal temperature sensor supplies the diode's temperature data for the temperature-compensation algorithm used by the power meter.



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Agilent Technologies offers a complete range of power measurement solutions for high-frequency applications. The next section of this course will present an overview of these solutions.

P-Series, EPM-P and EPM Series Power Meters

- **P-Series Power Meters**
  - Peak, average, peak-to-average ratio; time-gated measurements; rise time, fall time and pulse width; 30 MHz video bandwidth (N1911A/12A)

- **EPM-P Series Power Meters**
  - Peak, average, peak-to-average ratio; time-gated measurements, 5 MHz video bandwidth (E4416A/17A)

- **EPM Series Power Meters**
  - Average power measurements (E4418B/19B)

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With the introduction of the new P-Series power meters, Agilent now has three families of power meters addressing different markets and customer requirements.

The P-series meters and sensors provide peak and average power measurements on signals with up to a 30 MHz video bandwidth, while the EPM-P series were designed to perform peak and average power measurements on signals with up to a 5 MHz video bandwidth. Note that the video bandwidth, also called the modulation bandwidth, determines the detectable bandwidth of the modulating signal, and should not be confused with the RF bandwidth, which dictates what range of frequencies the sensor can measure. The EPM series power meters are specifically for conventional average power measurements.

8480, E-Series and P-Series Power Sensors

- **8480 Series (Diode and Thermocouple)**
  - Average power from – 70 to +44 dBm; 100 kHz to 110 GHz; unlimited video BW
  - Typical dynamic range of 50 dB

- **E-Series (Diode)**
  - **E441X:** 90 dB dynamic range; CW only
  - **E9300:** 80 dB dynamic range; average power of any signal type; no BW limitation
  - **E9320:** peak and average power from 50 MHz to 18 GHz; 5 MHz video BW

- **P-Series (Diode)**
  - **N192XA:** peak and average from 50 MHz to 40 GHz; 30 MHz video BW

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Agilent makes three series of power sensors — the 8480 series, E-Series and P-Series sensors. The 8480 series are thermocouple and diode sensors that provide average power measurements from – 70 dBm to +44 dBm and from 100 kHz to 110 GHz depending on the sensor chosen. They have unlimited modulation bandwidth and so can measure signals of any type. The typical dynamic range of these sensors is 50 dB.

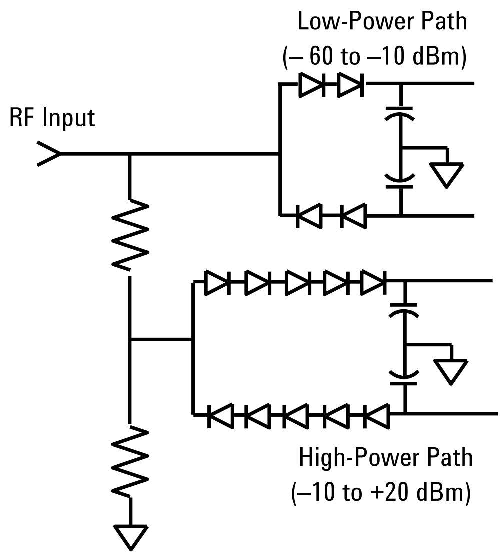
The E-Series diode power sensors all have calibration factors, linearity and temperature correction data stored in EEPROM, and provide measurements with up to a 90 dB dynamic range. E441X sensors are for Continuous Wave (CW) applications only.

The E9300 sensors provide wide dynamic range average power measurements on signals of any type, from simple CW to signals with complex digital modulation formats. These sensors are ideal for average power measurements on CDMA and W-CDMA signals, as they have no bandwidth limitation.

The E9320 sensors provide peak and average power measurements when used with the EPM-P series power meters on signals with up to 5 MHz video bandwidth.

The newer P-Series wideband sensors take peak and average power measurements to wider video bandwidth signals of up to 30 MHz when used with the P-Series power meters.

E9300 Average Power Sensor Technology



- 80 dB dynamic range with any signal type
- Two-path design
- Diode stack/attenuator/diode stack topology
- Automatic path switching

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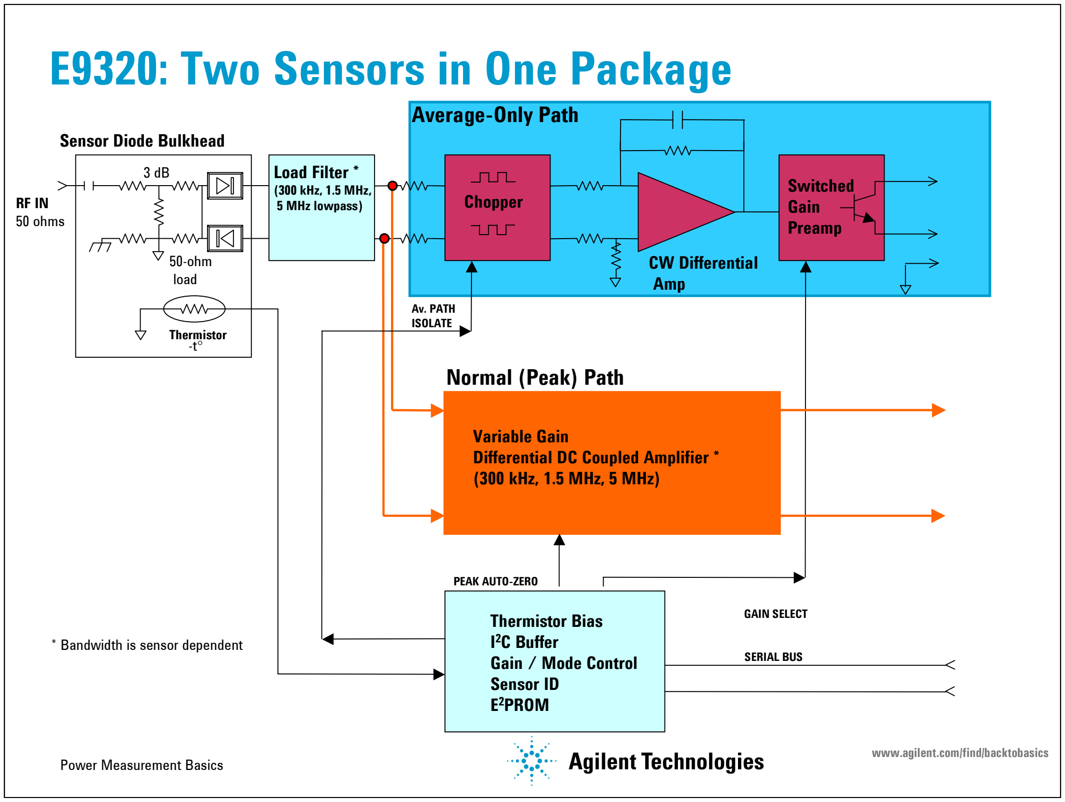
We've discussed sensor correction for CW signals, but what about for signals with complex modulation, such as CDMA? The E-series E9300 average power sensors are diode sensors that give 80 dB of dynamic range when measuring signals of any type. To get this dynamic range, a two-path design is used, with separate paths for low power and high power. This innovative design is based on a diode stack/attenuator/diode stack topology. The diode stack configuration extends square-law operation to higher power levels at the expense of sensitivity.

Each diode stack forms a measurement path. The low-power path is for –60 to –10 dBm, and the high-power path is for –10 to +20 dBm. Only one path is active at any time, and switching between paths is fast, automatic and transparent to the user.



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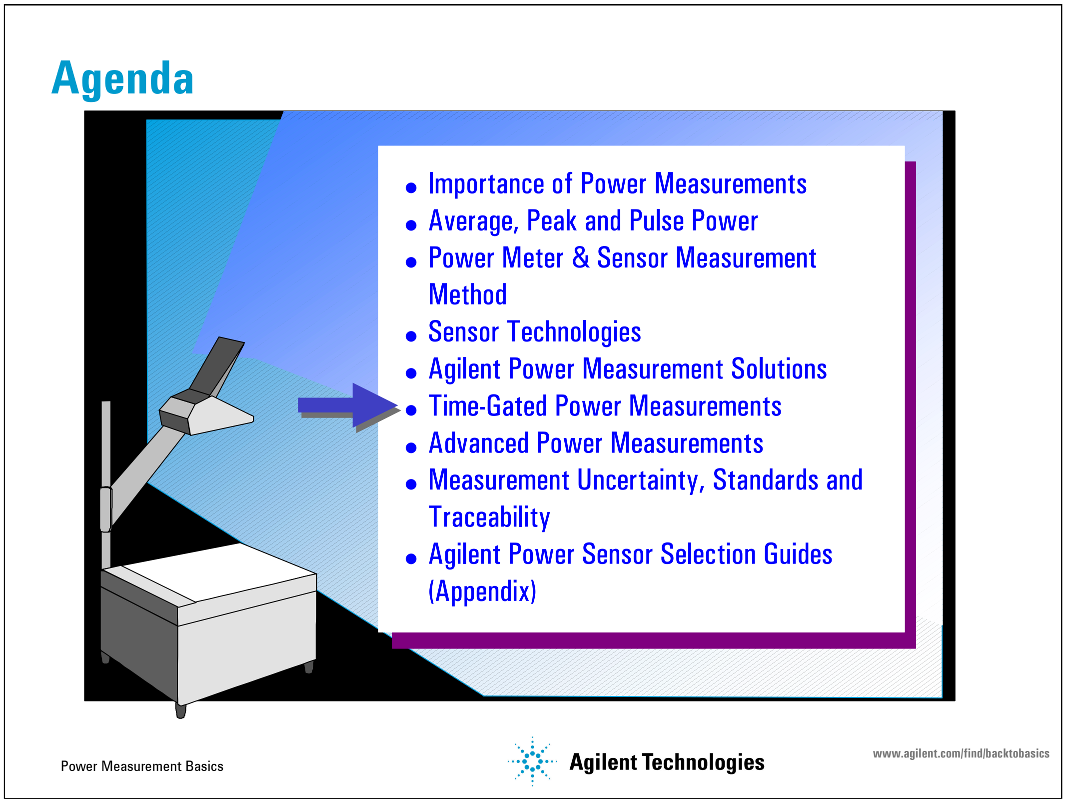
This slide shows a block diagram of an E-series E9320 peak and average power sensor. The signal processing is provided by two amplification paths, each optimized to their different data requirements. The E9320 sensors are designed for characterizing pulsed and complex modulation signals, and are compatible with the EPM-P and P-series power meters.



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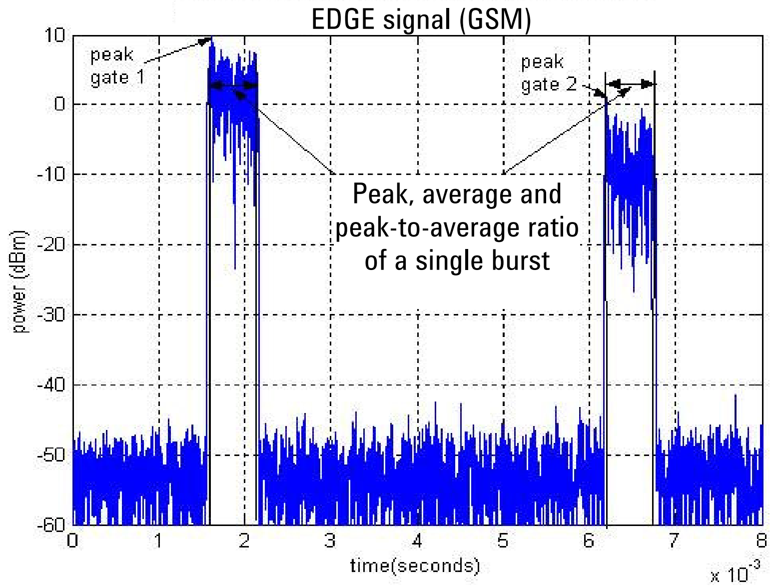
In the next section, we will look at time-gated power measurements, which are essential for modern wireless formats.

Time-Gated Power Measurements



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The capability to make peak, average and peak-to-average ratio measurements on a single burst is a core requirement of a power measurement system for the evolving TDMA and CDMA wireless standards. This time-gated measurement allows fuller characterization of signals like EDGE (Enhanced Data rates for GSM Evolution), which has an amplitude-varying modulation format within the RF burst, as shown on this slide.

Sensors for Time-Gated Measurements

- **Sensor rise/fall time requirements**
  - For characterizing overshoot: $\leq$ 1/8 signal rise time
  - For average power: same as signal rise time
- **E9320 peak/average sensors**
  - 200 ns rise time (typical)
  - TDMA, CDMA and W-CDMA wireless formats

- **P-Series wideband power sensors**
  - $\leq$ 13 ns rise time and fall time
  - Radar and pulsed component test

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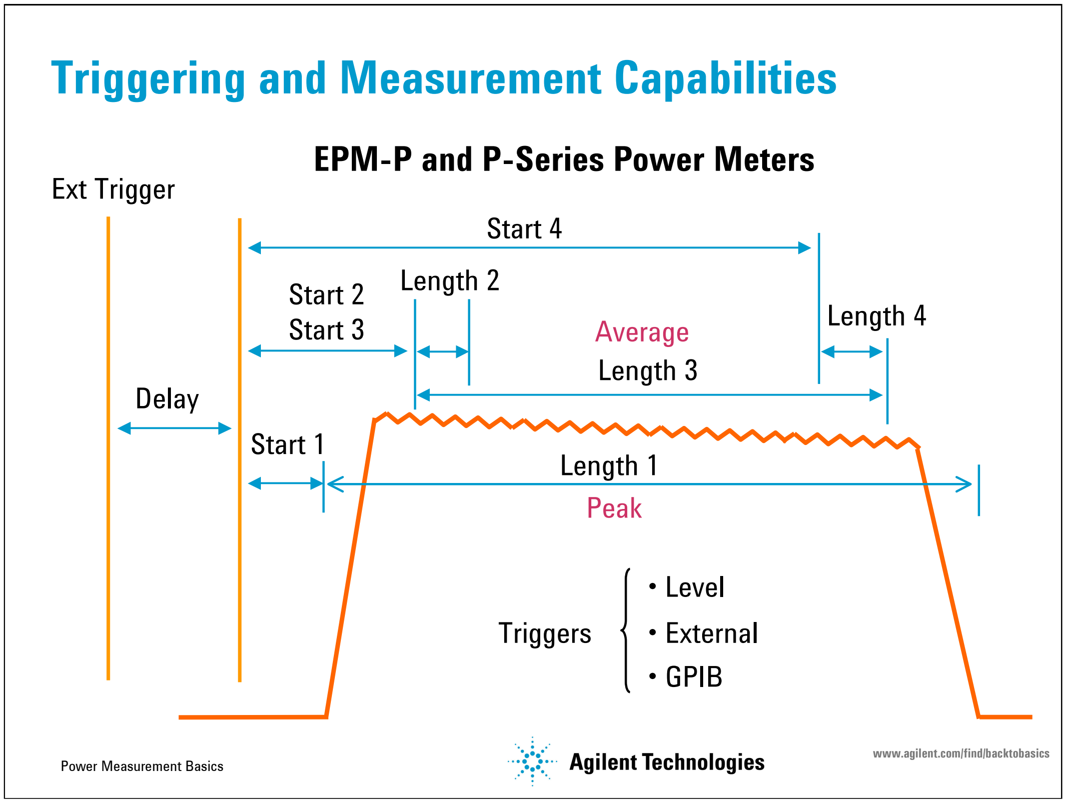
To make time-gated measurements of TDMA-type pulses, the measurement system must have sufficient rise and fall times. If overshoot is to be characterized, the power sensor's rise and fall times must be fast enough to follow the rising and falling edges of the signal ON period. It is generally recommended that the power sensor's rise time be no more than 1/8 of the expected signal's rise time. However, if only the time-gated *average* power is being measured, then a rise time similar to that of the signal can be used. Although the rising edge of the measured burst will be delayed from the rising edge of the signal, the start of the time-gated measurement can be delayed to account for this, allowing accurate time-gated average power measurements to be made.

The E9320 peak and average sensors have a typical rise and fall time of 200 ns (E9323A and E9327A 5 MHz video bandwidth sensors), making them ideal for wireless formats, and some radar and pulsed component test applications.

The P-Series wideband power sensors provide rise and fall times of less than or equal to 13 ns when used with a P-Series power meter, making them suited for radar and pulsed component test applications.



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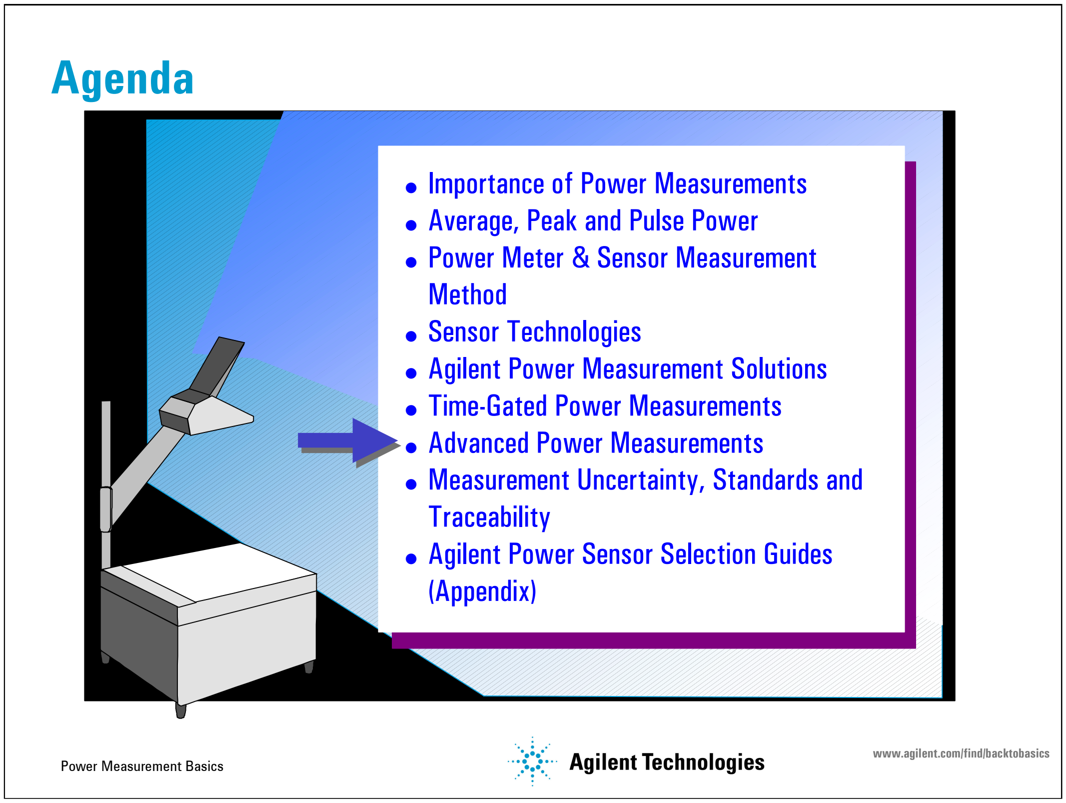
The EPM-P and P-series power meters have extensive triggering and time-gated measurement capabilities.

The triggering capabilities include level, external and GPIB triggering, plus the ability to have four separate measurements on a single burst. Four independent start delays and gate lengths can be set from the trigger event. Each of these four measurements, during the Length timeframe, can be set up to measure either peak, average or peak-to-average ratio. This allows users to measure the average power of a GSM signal over the 5% to 95% part of the burst, and the peak power over the complete timeslot. For the EDGE wireless format, this feature provides power measurements on the varying amplitudes that can be set up in different EDGE timeslots.



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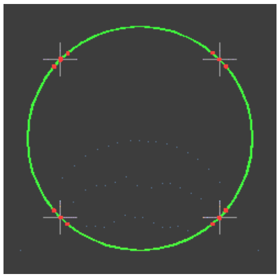
High-frequency systems and components are increasingly tested using the same types of complex signals that are found in their target applications, and they are tested to ensure compliance to exacting international standards. This has created a growing demand for advanced in-box and PC-based power measurements.

Technology Drivers

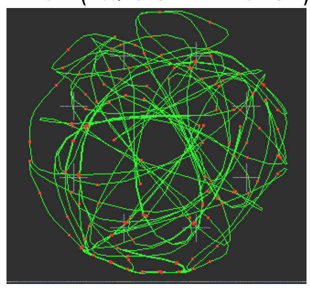
- **Aerospace and Defence (Radar)**
- **Digital Wireless Communications**

GSM (0.3 GMSK)



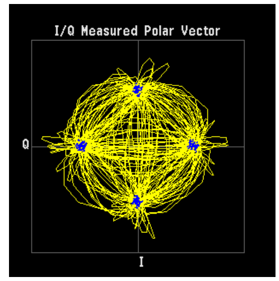
- TDMA system
- Time-gated average power
- Fast measurements

EDGE ($3\pi/8$ Shifted 8PSK)



- High-speed data transfer

cdma2000



- 3G technology
- Peak-to-average ratio
- CCDF

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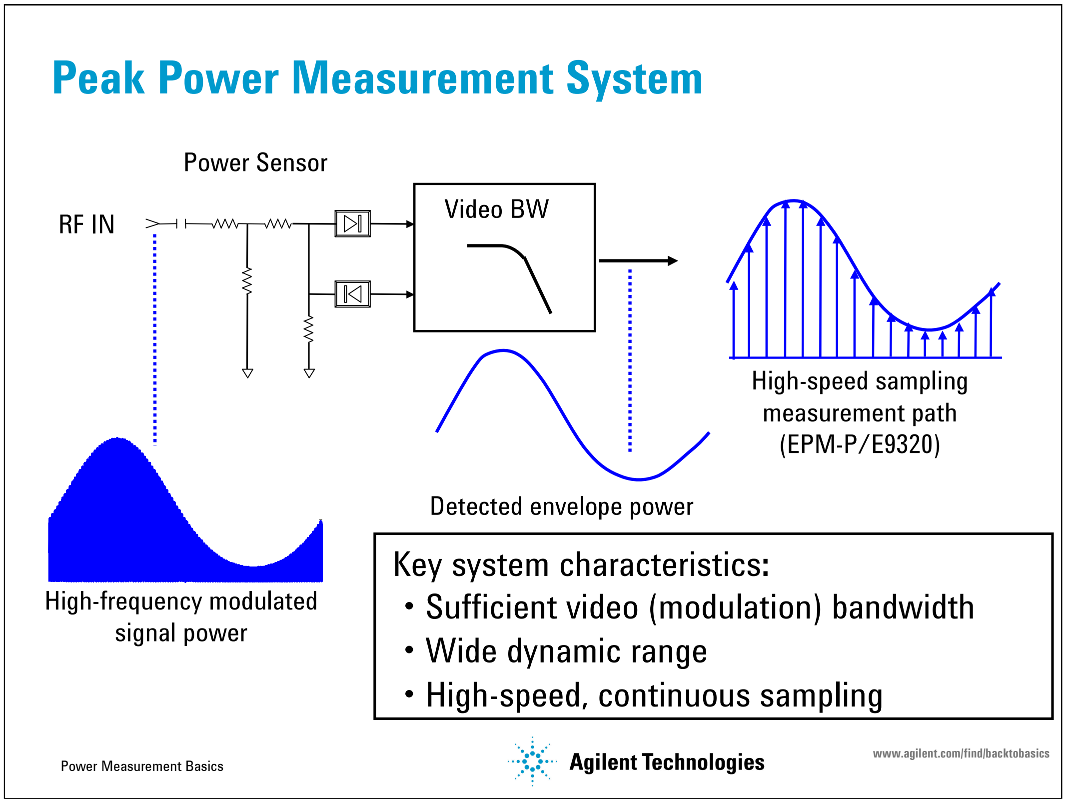
In the early 1990s, the main technology drivers for power measurements shifted from the Aerospace and Defense market, where accurate pulse power measurements of radar were needed, to digital wireless communications, with second generation (2G) technology and GSM coming to the fore. This constellation diagram from a vector signal analyzer shows the data states for a GSM signal, which uses GMSK (Gaussian Minimum Shift Keying) modulation.

GSM is a Time Division Multiple Access (TDMA) system requiring time-gated average power measurements over at least a 50 dB dynamic range. Fast measurement speeds for the high-volume manufacturing of RF and microwave components and systems is important for this market.

The demand for higher data rates has resulted in the emerging EDGE (Enhanced Data rates for GSM Evolution) system, which uses the 3-bit-per-symbol modulation scheme shown in this constellation display.

The move from second-generation to third-generation (3G) mobile phone technology starting in the late1990s introduced Code Division Multiple Access (CDMA) systems. Because both TDMA and CDMA signals have noise-like power spectra with similar power spikes, measurement requirements include peak-to-average ratio and average power, plus statistical power distribution information, such as the Complementary Cumulative Distribution Function (CCDF).



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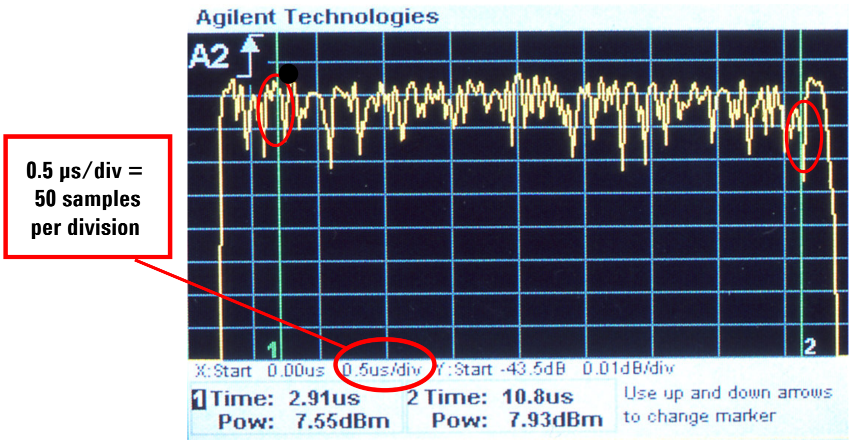
For complex, digitally modulated signals, such as wideband CDMA (W-CDMA), a nearly instantaneous measurement is required for an accurate determination of the peak power or peak-to-average ratio. This means that the power sensor must have sufficient video bandwidth to follow a fast-changing power envelope.

However, there is a tradeoff between video bandwidth and dynamic range. The wider the video bandwidth, the smaller the dynamic range. So, when choosing a sensor to measure a particular format with maximum dynamic range and minimum measurement uncertainty, a sensor with a video bandwidth just larger than the modulation bandwidth of the format should be selected.

In the case of the Agilent EPM-P power meters and E9320 sensors, the detected envelope power is input to a high-speed, continuous-sampling power measurement path. The detected power envelope is sampled at 20 MSamples per second, thus ensuring accurate pulse profiling of complex modulation formats, with up to 5 MHz video bandwidth.

Wide Bandwidth and Fast, Continuous Sampling

- **P-Series Power Meters and Sensors**
  - 30 MHz video bandwidth up to 40 GHz
  - Continuous sampling at 100 Msample/s



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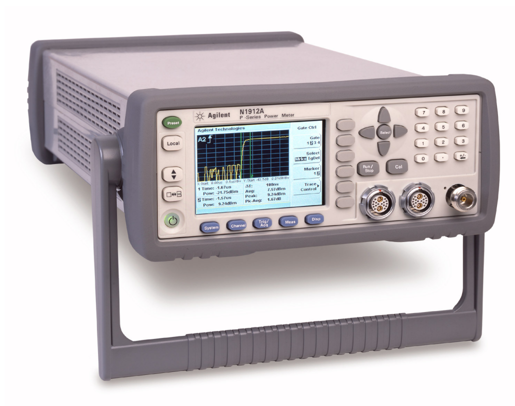
Modern radar and wireless communications systems demand more exacting power measurements over wider bandwidths than ever before. With the introduction of the P-series power meters and sensors, Agilent has a power measurement system that can measure signals up to 40 GHz with a 30 MHz video bandwidth, and continuous sampling at 100 MSample/s.

The wide video bandwidth and fast, continuous sampling enable users to capture single-shot events and perform repeatable and accurate measurements of peak and average power. In this example, the trace markers indicate the peak power at two different points on a single pulse.

P-Series Power Meters and Sensors



- **Key Measurements**
  - Peak, average, peak-to-average ratio; rise time, fall time and pulse width; time-gated and free-run measurements

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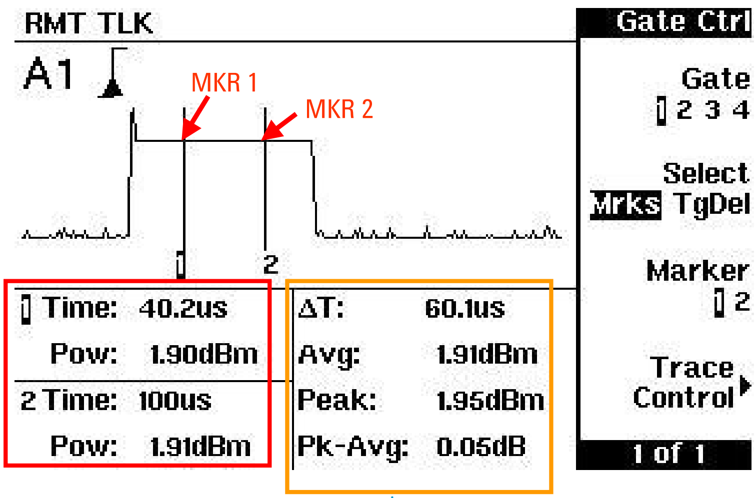
In addition to the standard measurements of peak, average and peak-to-average ratio, the P-series meters and sensors can also perform time measurements such as rise time, fall time and pulse width.

EPM-P Series Measurement Display

- Graphical trace setup
- Marker measurements and analysis



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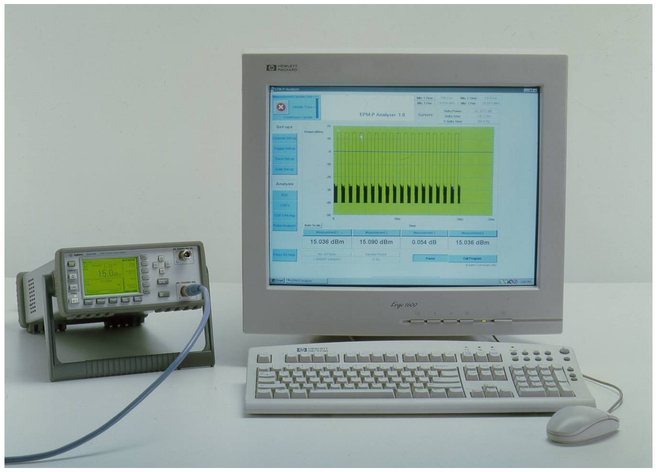
The ability of the EPM-P series power meters to make advanced in-box measurements is illustrated by the instrument screen shown here. This display provides graphical trace setup, with marker measurements and analysis. In this example, a pulse profile is shown, with the variable markers 1 and 2 providing the instantaneous power and time relative to the trigger event. The analysis section of the display shows the delta time, delta average, delta peak and delta peak-to-average power ratio with respect to markers 1 and 2.

EPM-P Analyzer Software

- A PC-based tool for pulse and statistical analysis
- CDMA, TDMA and radar signals



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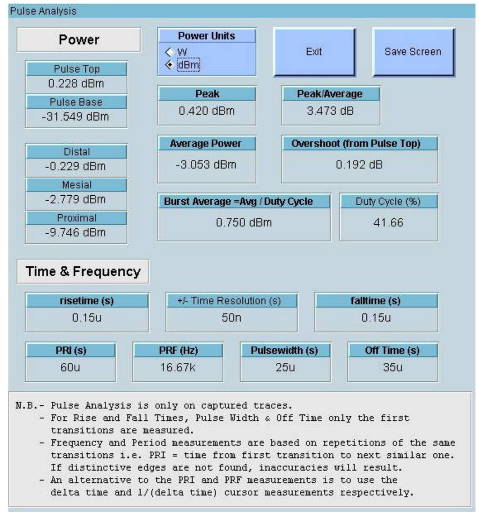
Agilent offers more extensive power measurements and features in a PC environment.
This slide shows the EPM-P analyzer software operating via the GPIB to provide the statistical, power, frequency and time measurements that are required for CDMA, TDMA and pulsed radar signals.

Pulse Analysis

- **Power**
  Pulse Top, Pulse Base, Distal, Mesial, Proximal, Peak, Average, Peak/Average Ratio, Burst Average and Duty Cycle

- **Time and Frequency**
  Rise Time, Fall Time, Pulse Repetition Frequency (PRF), Pulse Repetition Interval (PRI), Pulse Width and Off Time

* IEEE pulse definitions and standards for video parameters applied to microwave pulse envelopes (ANSI/IEEE Std. 194-1977).



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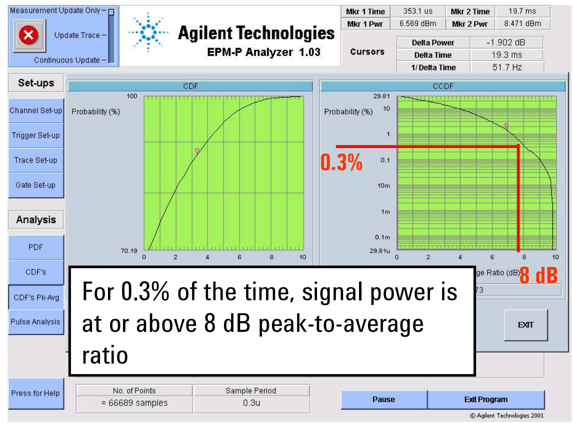
This is the Pulse Analysis menu of the EPM-P analyzer software, which computes many power, time and frequency parameters.

Statistical Analysis

- **Statistical Functions**
  - Cumulative Distribution Function (CDF)
  - Complementary Cumulative Distribution Function (CCDF)
  - Probability Density
- **CCDF**
  - Complete power characterization
  - Helps optimize system design



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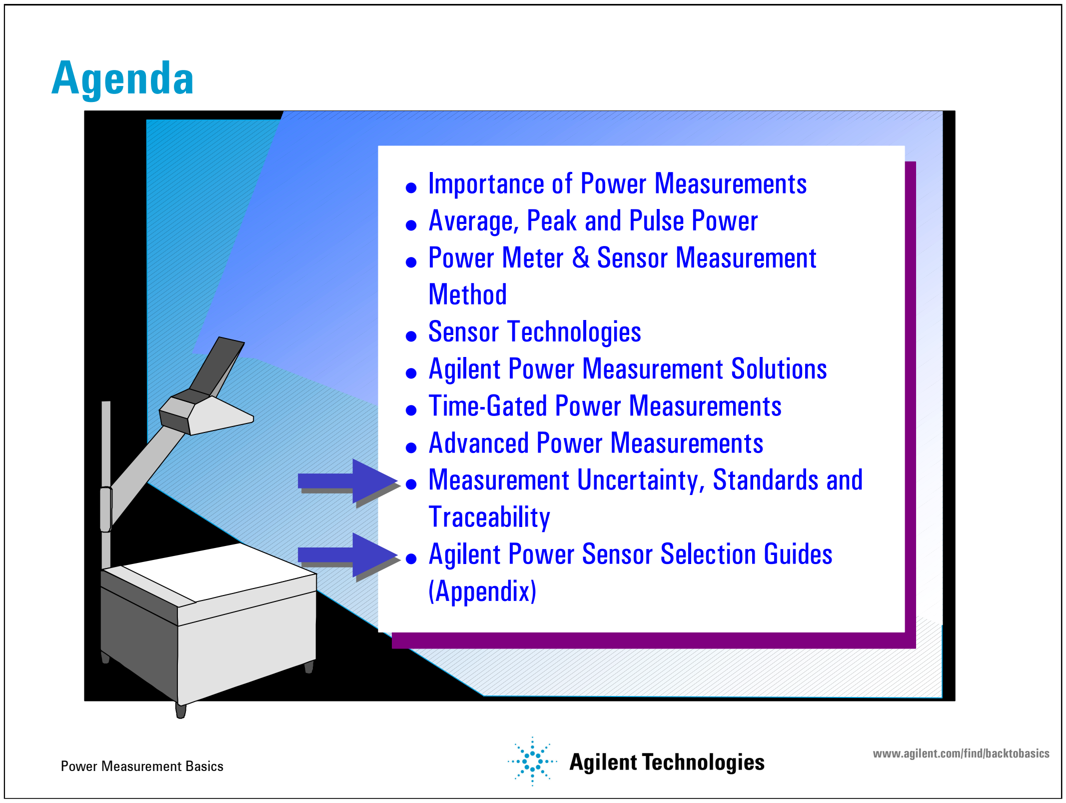
The EPM-P analyzer software provides several statistical functions, including the Complementary Cumulative Distribution Function, or CCDF, which is probably the most important. The CCDF can completely and unambiguously specify the power characteristics of the signals that will be amplified, mixed and decoded in communication systems.

For CDMA signals, the statistical analysis of the power distribution can reveal important information to help optimize system design. For example, statistical data can reveal how a system or device, such as a power amplifier, may be distorting the signal that it's transmitting. Comparison of the CCDF plots from an amplifier at differing average power levels validates the linearity and reveals the introduction of data errors that can be caused by signal compression.

For this CCDF curve, as shown by the red lines, the signal spends 0.3% of its time at or above the average power plus 8 dB.



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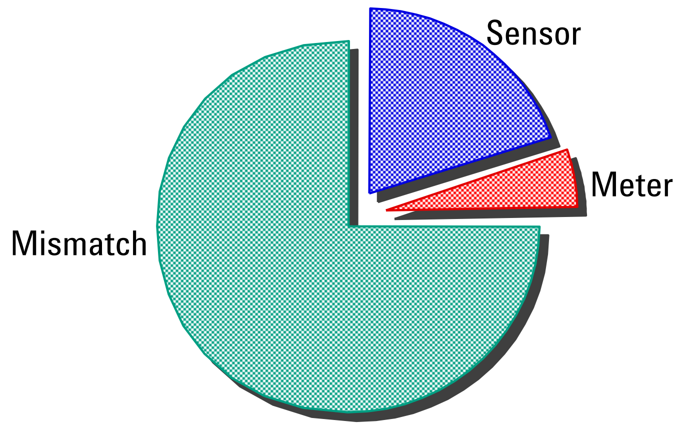
Now we will cover the final topic in this course: the uncertainty and traceability of power measurements. There is an appendix at the end of this course that consists of a set of power sensor selection guides. These guides will not be discussed in the course, but they may be useful as a reference for you later.

Sources of Power Measurement Uncertainty

- **Sensor and Source Mismatch Errors**
- **Power Sensor Errors**
- **Power Meter Errors**



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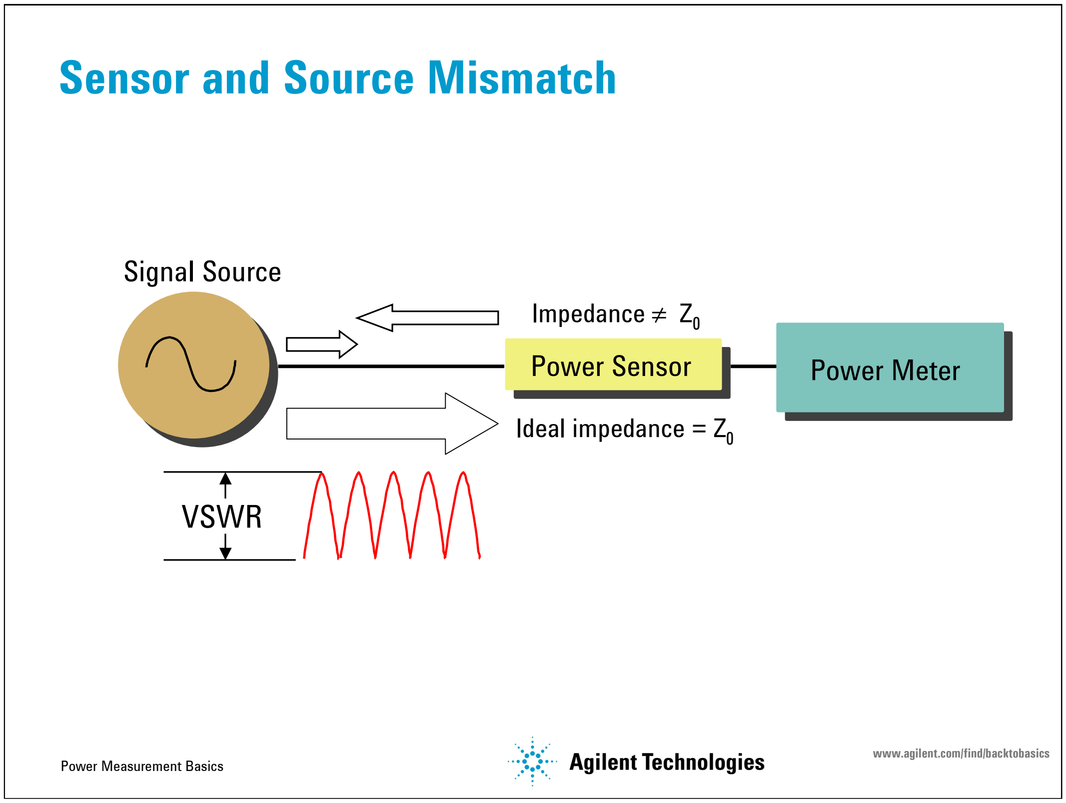
In power measurements, as in all measurements, there are many sources of uncertainty, or error. Sensor and source impedance mismatch typically causes the largest error. The second largest source of error are the uncertainties associated with the power sensor, and the third most significant contribution are errors associated with the power meter. Let's analyze the various uncertainties associated with power measurements, and then look at an example combining all errors for a total uncertainty calculation.



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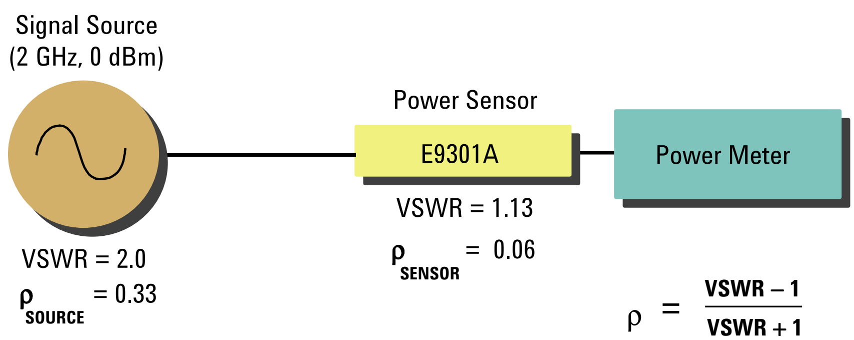
In a power measurement, we are usually interested in the power delivered to a reference impedance, Z_0, so ideally the power sensor's impedance would be Z_0. When the sensor impedance is exactly Z_0, none of the signal reflects from the sensor but rather is completely absorbed. Any time that the sensor impedance deviates from Z_0, the sensor is mismatched and reflections will occur. This means that a portion of the source power never reaches the sensing element and therefore cannot be measured. Similarly, the source will typically be mismatched and reflections will also occur there. Phase addition and subtraction of the incident and reflected waves creates a voltage standing wave pattern on the transmission line. The ratio of the maximum to minimum voltage is the Voltage Standing Wave Ratio, VSWR. Although the exact power entering the sensor cannot be determined, the maximum and minimum values of the power can be calculated from the VSWR of the source and sensor.

Calculation of Mismatch Uncertainty



$$\rho = \frac{VSWR - 1}{VSWR + 1}$$

$$\text{Mismatch Uncertainty} = \pm 2 \times \rho_{SOURCE} \times \rho_{SENSOR} \times 100\%$$

$$= \pm 2 \times 0.33 \times 0.06 \times 100\% = \boxed{\pm 3.96\%}$$

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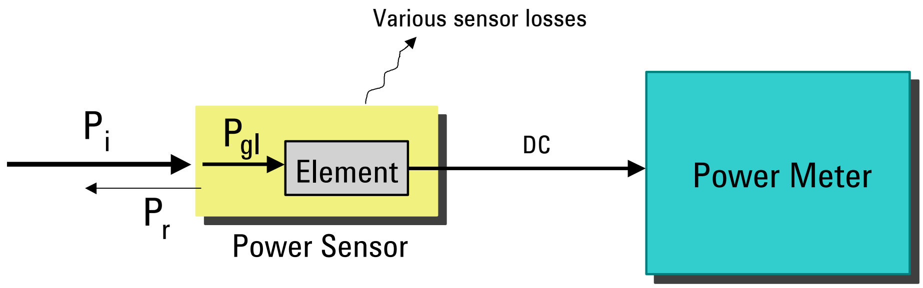
In this example, the Agilent E9301A Power Sensor has a VSWR of 1.13 at 2 GHz and the source has a VSWR of 2.0. We first determine the reflection coefficient, ρ (rho), for sensor and source from the respective VSWRs. The mismatch uncertainty percentage is then found by using this equation. In this example, the mismatch contributes +/-3.96% uncertainty to the measurement.

We will use this calculated value of mismatch error in determining the overall measurement uncertainty.

Power Sensor Uncertainties



Cal Factor : $K_b = \eta_e \dfrac{P_{gl}}{P_i}$ (η_e = Effective Efficiency)

- Printed on sensor label (8480 series)
- Stored in EEPROM (E-series and P-series)

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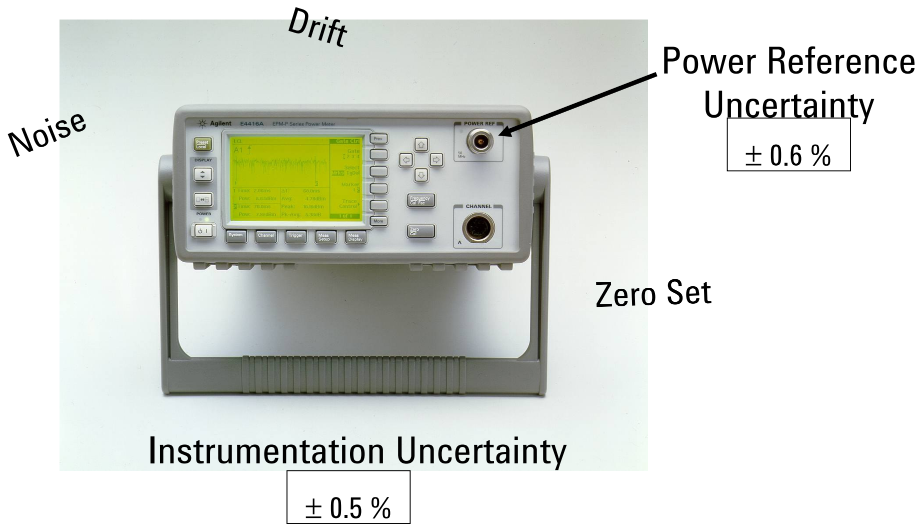
For a power sensor, the "power in" (Pgl) is the net power delivered to the sensor. It is the incident power (Pi) minus the reflected power (Pr); however, not all the input power is dissipated in the sensing element. For example, some of the power is turned into heat in other parts of the sensor. The metered power indicates only the power that the sensing element itself dissipates.

Calibration factor, K_b, takes into account the imperfect efficiency of the sensor and the mismatch loss, which accounts for the reflected signal. The calibration factor is unique to each sensor and is determined by the manufacturer during the production test process. The calibration factor is either printed on the power sensor label, as with the Agilent 8480 series sensors, or stored in EEPROM as in the Agilent E- and P-series sensors. A calibration sheet containing the sensor's unique calibration factor and reflection coefficient data is shipped with each sensor.

Power Meter Instrumentation Uncertainties



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There are several uncertainties associated with the electronics inside the power meter. These uncertainties should be included for a complete uncertainty analysis, although they are typically smaller than the source sensor mismatch and other sensor uncertainties. The most significant of these uncertainties are usually specified in two groups, power reference uncertainty and instrumentation uncertainty.

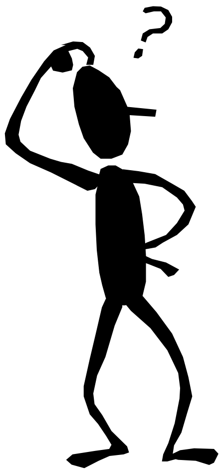
<u>Power reference uncertainty</u>

Thermocouple and diode sensors require a highly accurate, known power source to verify and adjust for the sensitivity of the individual sensor. Agilent power meters have as standard a 1.0 mW, 50 MHz calibration source. The power reference uncertainty is the uncertainty in the output level of this calibration source. The specified power reference uncertainty is +/-0.6% for two years at 25 +/- 10 degrees C.

<u>Instrumentation uncertainty</u>

Instrumentation uncertainty is the combination of such factors as meter tracking, circuit nonlinearities and amplifier gain uncertainties. The instrument manufacturer guarantees the accumulated uncertainty is within a certain limit. For example, the instrumentation uncertainty for the EPM and EPM-P series power meters is specified as +/- 0.5% for absolute average power measurements.

What is an Acceptable Measurement Uncertainty?



- Which is the smaller error: ± 1.0 dB ... or ± 20% ?

  ➡ Answer: ± **20% !**

  (± 1.0 dB is + 26%, – 21%)

- Sensor and meter uncertainties are specified in percentage (linear) and dB (log)

- Marketing Manager's Law of Small Numbers:

  "A small-numbered uncertainty specification sounds better than a large-numbered one."

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In an informal poll, six test engineers stated that an error of ± 1.0 dB was acceptable, but dismissed a ± 20% error as unacceptable. However, an error of 20% is actually *less* than a 1.0 dB error, which in percentage terms is + 26%, -21%.

Uncertainties for power sensors and meters are usually specified linearly as percentages for ease in calculating total measurement uncertainly, and often in dB as well to satisfy the"Marketing Manager's Law of Small Numbers," which states that a small-numbered uncertainty specification sounds better than a large-numbered one.

Now let's see how the power measurement uncertainties we've discussed are combined to arrive at the total measurement uncertainty.

Calculating Power Measurement Uncertainty

1. Identify significant uncertainties

- Mismatch uncertainty: ± 3.96%
- Power linearity: ± 2.0% [1]
- Cal factor uncertainty: ± 1.8% [1]
- Power reference uncertainty: ± 0.6% [1]
- Instrumentation uncertainty: ± 0.5%

[1] Specifications apply for an E9301A sensor and Agilent power meter over a temperature range of 25 ±10 degrees C.

2. Combine uncertainties

- Worst-case or Root Sum of the Squares (RSS) method

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The first step in calculating overall measurement uncertainty is to identify all the significant sources of error. These are the significant uncertainties for our example measurement with the E9301A power sensor and Agilent power meter measuring a 2 GHz signal at 0 dBm, taken from the technical specifications for these products. The mismatch uncertainty is calculated from the specified SWR of the source and the sensor, as shown previously. The calibration factor uncertainty is specified at different frequency points within the range. At a power level of 0 dBm, zeroing errors and noise are not significant.

After all the uncertainties have been identified, we next determine how these uncertainties act together to affect the final measurement result. We'll now look at two methods that are commonly used to combine power measurement uncertainties: worst-case and Root Sum of the Squares, or RSS.

Worst-Case Uncertainty

- **Worst-case situation is assumed**
  - All sources of error at their extreme values
  - Errors add constructively
- **In our example measurement:**

3.96% + 2.0% + 1.8% + 0.6% + 0.5% = ± 8.86%

Or, in log terms:

+ 8.86% = 10 log (1 + 0.089) = + 0.37 dB

– 8.86% = 10 log (1 - 0.089) = – 0.40 dB

- **Extremely conservative**

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One way of determining the total error of a power measurement is the worst-case uncertainty method. The worst-case situation would occur if all the possible sources of error were at their extreme values, and added together constructively to achieve the maximum possible deviation between the measured and actual power values.

In our example, the worst-case approach results in an uncertainty of +/- 8.86%, or + 0.37, - 0.40 dB.

It is VERY unlikely that all errors will add together constructively, making this worst-case scenario extremely conservative. A more realistic method of combining uncertainties is the Root Sum of the Squares, or RSS method.

RSS (Root Sum of the Squares) Uncertainty*

Source of Uncertainty	Value (± %)	Probability Distribution	Divisor	Standard Uncertainty u_i (k=1)
Source/Sensor Mismatch at 2 GHz	3.96	U-shaped	1.414	2.8
Calibration Factor Uncertainty at 2 GHz	2.0	Normal	2	1.0
Linearity at 0 dBm	1.8	Normal	2	0.9
Power Reference Uncertainty	0.6	Normal	2	0.3
Instrumentation Uncertainty	0.5	Normal	2	0.25

Combined Standard Uncertainty = u_c = RSS of u_i

* In accordance to guidelines published in the *ISO Guide to the Expression of Uncertainty in Measurement* and ANSI/NCSL Z540-2-1996, *US Guide to the Expression of Uncertainty in Measurement.*

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A more realistic approach to combining uncertainties is the RSS method. It is based on the fact that most of the errors, although systematic, are independent of each other and so combine like random variables. This allows us to use the statistical combination called Root Sum of the Squares.

The table summarizes the statistical characteristics of each source of uncertainty. Each uncertainty percentage is normalized to a one sigma value by dividing it with a divisor that is determined by the probability distribution of the uncertainty. The divisor is 2 for a normal distribution, the square root of 3 for a rectangular distribution, and the square root of 2 for the unusual U-shaped distribution of source/sensor mismatch. The one sigma value is called the standard uncertainty, u_i

The combined standard uncertainty, u_c **,** is defined as the Root Sum of the Squares of the individual standard uncertainties.

Combined Standard Uncertainty (u_c)

- **In our example:**

$$u_c = \sqrt{(2.8)^2 + (1.0)^2 + (0.9)^2 + (0.3)^2 + (0.25)^2}$$

$$= \pm 3.13\%$$

- **Expanded uncertainty (k = 2)**

$$= k \times u_c = \pm 6.26\%$$

$$= 10 \log (1 + 0.063) = +0.27 \text{ dB}$$

$$10 \log (1 - 0.063) = -0.28 \text{ dB}$$

Worst-case

+ 0.37 dB

– 0.37 dB

- **Agilent AN 1449-3 covers uncertainty calculations**

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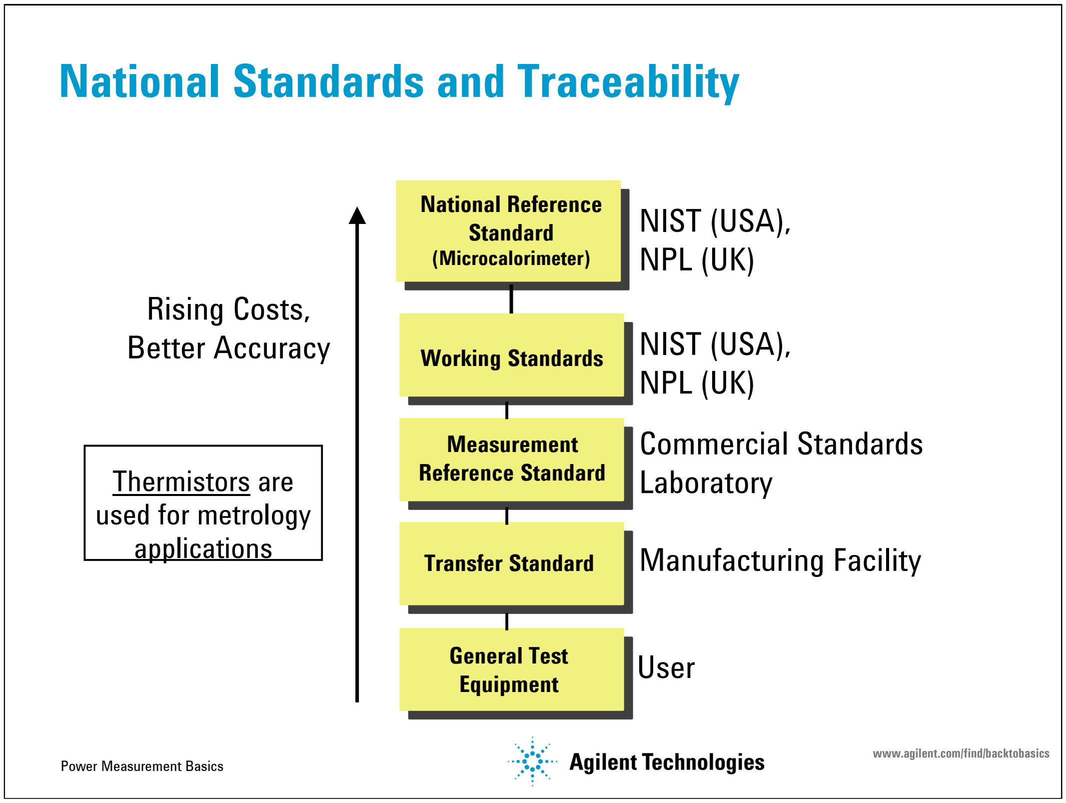
Once all the individual sources of uncertainty have been normalized for one sigma, the combined standard uncertainty is calculated as the square root of the sum of the squared uncertainty values. The result for our example is ± 3.13 %.

The expanded uncertainty is the combined standard uncertainty times the coverage factor, k. The coverage factor is like a guard band, and the value chosen depends on the level of confidence required for the specification. A coverage factor of 2 provides a confidence level of 95.45%, and a factor of 3 provides 99.73% confidence. For a coverage factor of 2, the expanded uncertainty for our example measurement is therefore ± 6.26%, or +0.27, –0.28 dB. This contrasts favorably with the pessimistic worst-case analysis.

The calculation of power measurement uncertainties is covered in detail in Agilent Technologies Application Note 1449-3, *Fundamentals of RF and Microwave Power Measurements (Part 3)*.



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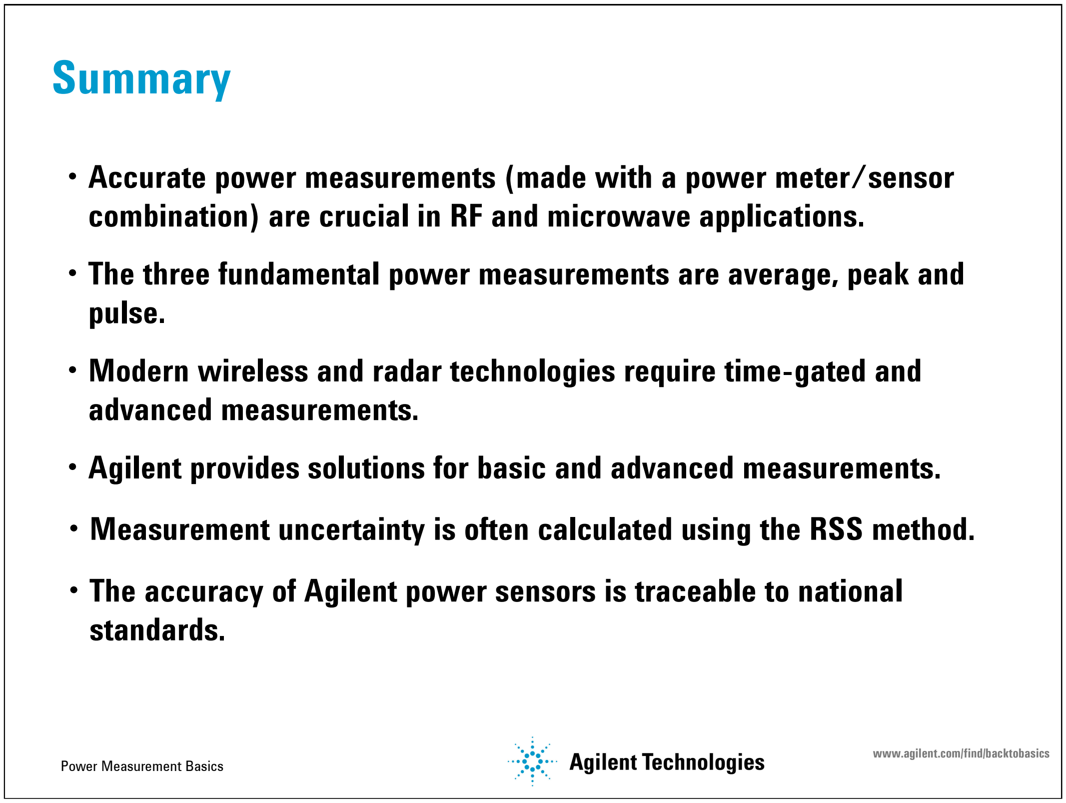
It's important to ensure that power measurements can be duplicated at different times and at different places. This requires well-behaved equipment, excellent measurement technique, and a universally accepted reference standard for the watt. The U.S. National Institute for Standards and Technology (NIST) in Boulder, Colorado maintains the National Reference Standard in the form of a microwave microcalorimeter. A similar standard is provided by the National Physical Laboratory (NPL) in the UK, and other standards organizations throughout the world.

A power sensor referenced back to national standards in the USA is said to be traceable to NIST. The normal path of traceability for a power sensor is shown in this diagram. At each level, at least one power standard is maintained for the frequency band of interest. That power standard is periodically sent to the next higher level for re-calibration, then returned to its original level. Rigorous measurement assurance procedures are used at the highest level, as any error at that point must be included in the total uncertainty at every lower level; thus, the cost of calibrations at the national standard level is usually the greatest.

To transfer power parameters such as calibration factor, effective efficiency and reflection coefficient, national standards organizations invariably use thermistor mounts, both coaxial and waveguide. This makes thermistor sensors the top choice for most metrology applications.



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Let's quickly review the key ideas we've covered in this course. First, accurate measurements of power are critical in most RF and microwave applications, and the power meter and power sensor combination is the most accurate and convenient way to make these measurements. The three basic types of power measurements are average, peak and pulse power. The advent of complex digital modulation schemes for wireless and radar technologies has created the need for time-gated measurements of these basic power types, as well as sophisticated inbox and PC-based statistical and pulse measurements. Agilent Technologies offers a complete range of power meter and sensor solutions to meet these power measurement requirements. Total measurement uncertainty is frequently calculated by determining specified meter and sensor uncertainties, computing source/sensor mismatch error, and then combining these using a statistical method called Root Sum of the Squares, or RSS. And lastly, the accuracy of Agilent power sensors is traceable to power standards maintained by national standards organizations.

For More Information

- Agilent Website
  - URL: http://www.agilent.com/find/powermeters
- Agilent Literature
  - Application Note AN 1449–1, 2, 3 and 4, *Fundamentals of RF and Microwave Power Measurements (Parts 1, 2, 3 and 4).*
  - Product Note, *Choosing the Right Power Meter and Sensor* (Lit. No. 5968-7150E).

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Agilent has several resources for more information on all aspects of high-frequency power measurements. This section of the Agilent Website is the best place to find descriptions and technical data for all of the company's power measurement solutions. Application Note AN 1449 covers every aspect of power measurement in four separate sections, and this Product Note is a comprehensive selection guide for Agilent power meters and sensors.

Appendix:

Power Sensor Selection Guides

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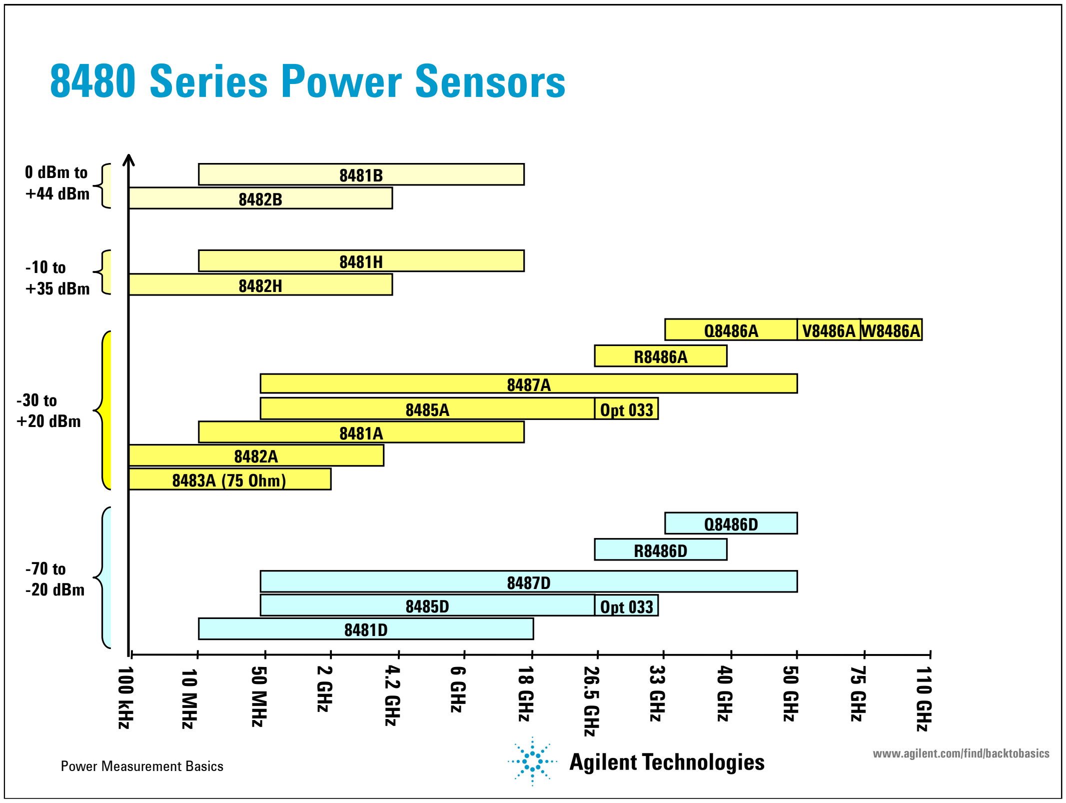
Appendix



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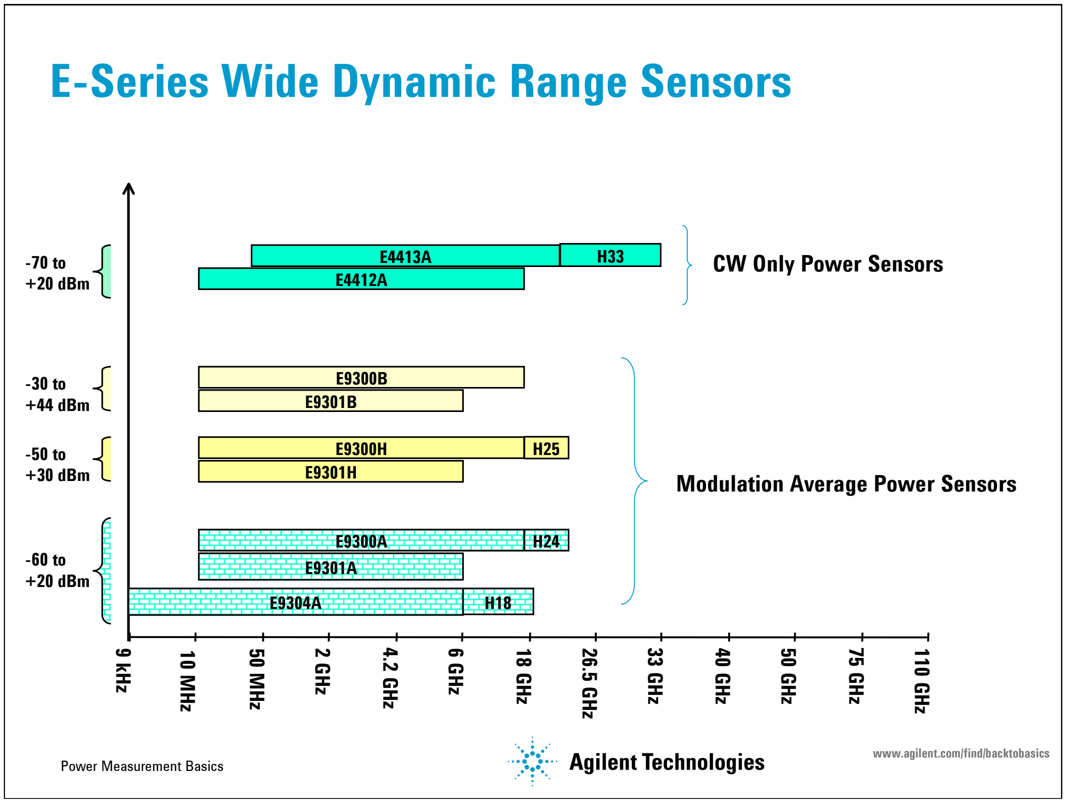
This graph shows the available 8480 series power sensors.



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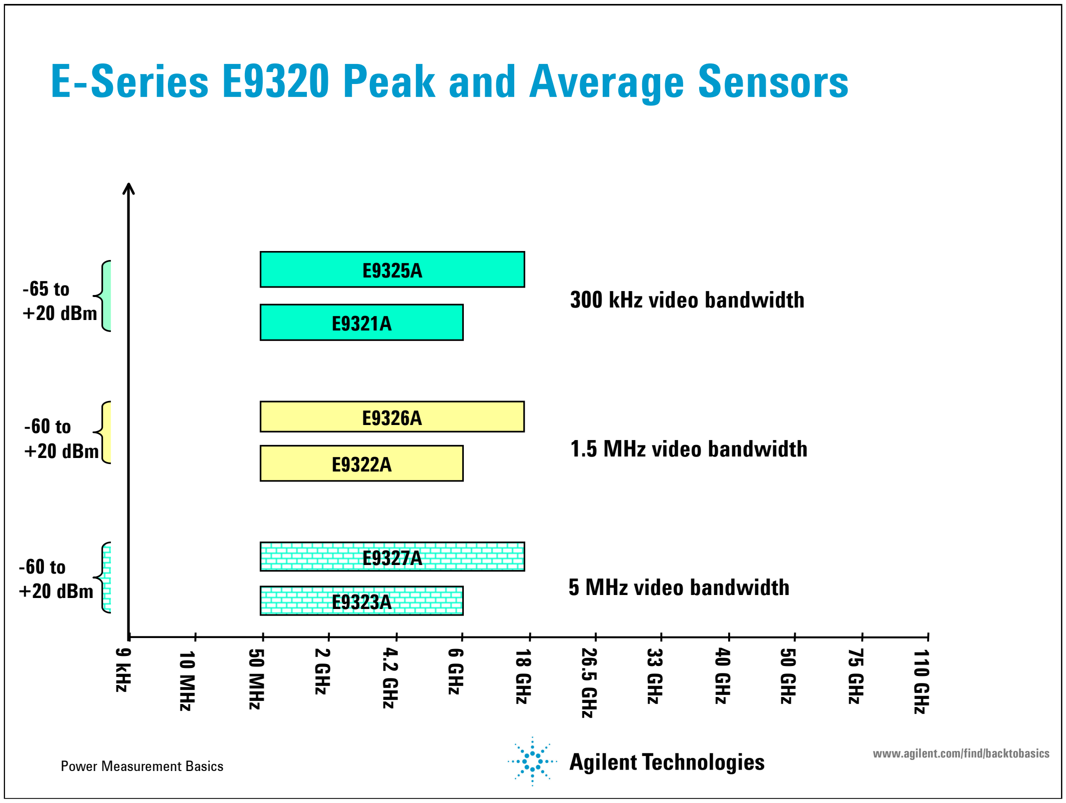
This graph shows the available E-Series wide dynamic range power sensors.



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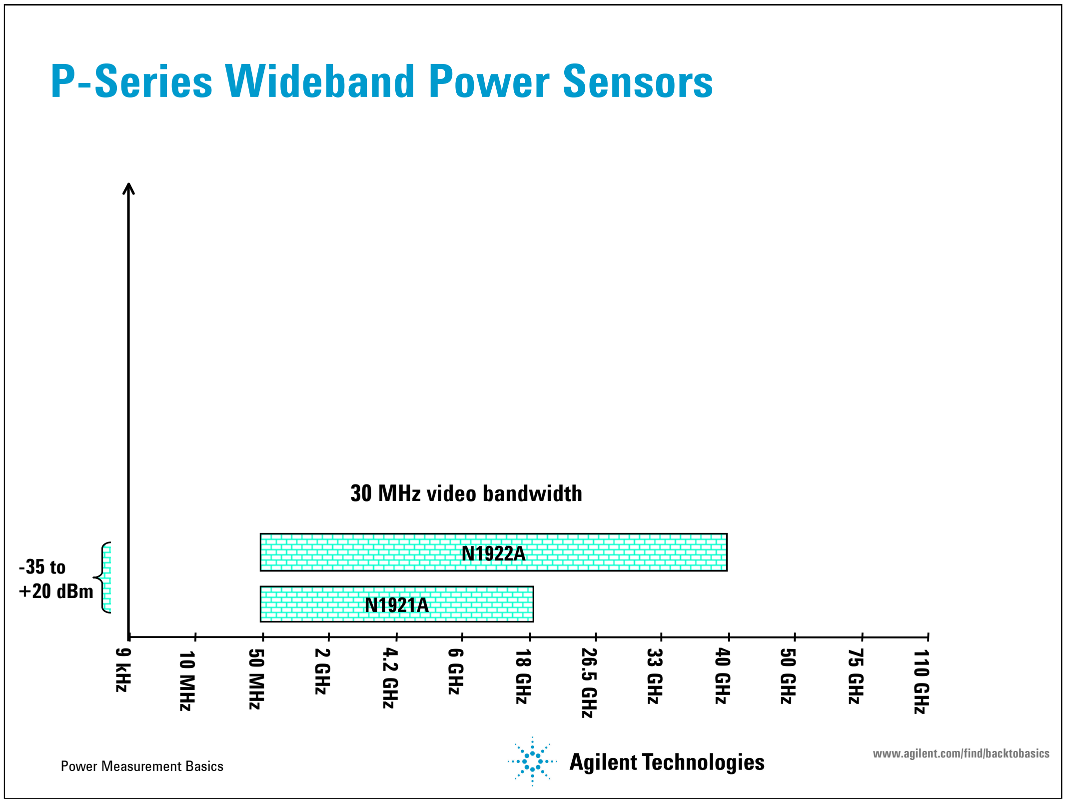
This graph shows the available E-Series peak and average power sensors.



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This graph shows the available P-Series wideband power sensors.

Quiz

1- Power is defined as;

a) Energy transferred per unit time
b) Amperes per second
c) 10 log(V/I)

2- The dB (decibel) compares two power levels on what type of scale?

a) Linear
b) Exponential
c) Logarithmic

3- The three basic types of power measurements are:

a) Average, Peak-to-Average and Envelope
b) Average, Peak and Pulse
c) Average, Instantaneous and Pulse

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Ready for a Quiz ?

Quiz

4- The output power level of a high-frequency system is:

- a) More difficult to measure than the voltage along the transmission line
- b) Typically the most important factor in determining its performance
- c) Less useful to measure than the output voltage

5- The most accurate instrument for measuring power is:

- a) A vector signal analyzer
- b) A power meter/sensor combination
- c) A spectrum analyzer

6- A power sensor:

- a) Detects the frequency of the modulating signal
- b) Can only measure digitally modulated signals
- c) Converts RF power to a DC or low-frequency signal

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Quiz

Quiz

7- The most widely used types of sensors are:

a) Diode detector and thermocouple
b) Thermistor and peak power
c) Thermocouple and wideband

8- Thermocouple power sensors:

a) Can only measure TDMA and CDMA signals
b) Can measure all types of signals
c) Can only measure CW signals

9- The P-series power meters:

a) Are specifically designed for average power measurements
b) Provide peak and average power measurements
c) Use an innovative two-path design

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Quiz

Quiz

10- The typical dynamic range of 8480 series average power sensors is:

a) 90 dB
b) 30 dB
c) 50 dB

11- Calibration data for individual E-series power sensors is:

a) Stored in EEPROM in the sensor
b) Downloadable from the Agilent Website
c) Printed on the sensor label

12- The 80 dB dynamic range of E-series E9300 average power sensors is achieved by the use of:

a) Advanced, thin-film thermocouples
b) Diode stacks and a two-path design
c) A 30 MHz video bandwidth

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Quiz

Quiz

13- Time-gated measurements:

a) Require the power sensor to have two measurement paths

b) Cannot be used to measure radar signals

c) Allow peak and average measurements to be made on a single burst

14- To make time-gated peak power measurements of TDMA-type signals:

a) A power meter must have a video bandwidth of at least 100 MHz

b) A power sensor must have a built-in reference oscillator

c) A power sensor's rise time must be fast enough to follow the rising edge of the signal burst

15- CDMA signals:

a) Require statistical power distribution information for complete characterization

b) Can be fully characterized by time-gated average power measurements

c) Are being superseded by 2G technology

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Quiz

Quiz

16- The EPM-P power meters:

a) Should only be used with P-series sensors
b) Are designed to measure only TDMA-type signals
c) Have high-speed, continuous sampling of the detected power envelope

17- The most significant source of power measurement uncertainty is usually:

a) Power sensor inefficiency
b) Sensor and source impedance mismatch
c) Instrumentation uncertainty

18- The most realistic method for combining measurement uncertainties is:

a) The worst-case method
b) The U-shaped probability distribution
c) The Root Sum of the Squares method

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Quiz

Quiz - Answers

1- a	10- c
2- c	11- a
3- b	12- b
4- b	13- c
5- b	14- c
6- c	15- a
7- a	16- c
8- b	17- b
9- b	18- c

Power Measurement Basics

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Answers to quiz questions. How did you do ?

Thank you for participating in Agilent's 2005 Back-to-Basics Seminar.