Test Specification

HART Field Communications Protocol

HART®
COMMUNICATION FOUNDATION

FSK Physical Layer Test Specification

HCF_TEST-2, Revision 2.2

Release Date: June 28, 2001

ERRATA - HART FSK Physical Layer Test Specification

The FSK Physical Layer Test Specificatio has been revised to revision 2.2 to singularly identify the inclusion of thedocument errata contained within the adjacent pages. No other modification was made to the document.

ERRATA - HART FSK Physical Layer Test Specification

This Errata provides guidance for proper testing of the HART FSK Physical Layer with respect to requirements for Carrier Stop/Carrier Decay timing, time from Carrier On to Start of First Character, and time from Last Character to Carrier Off. Requirements for these parameters were inadvertently omitted or relaxed in FSK Physical Layer Specification, HCF_SPEC-54, Revision 8.1 and unfortunately, were not discovered prior to the specification release.

This document will be revised along with the FSK Physical Layer Specification to reflect proper test methods and procedures for the requirements outlined below. Requirements for Carrier Stop/Carrier Decay timing are properly reflected in this document (Section 13.2) and the test data sheets. Requirements for Character Start/Stop testing will be incorporated into the next revision. Manufacturers are responsible to test their devices based on the requirements of this Errata.

Carrier Stop/Carrier Decay Requirements

Carrier Stop and Decay Timing in Revision 8.1 was inadvertently made less restrictive than Revision 8.0, taking time away from the Data Link Layer. The proper requirements for these parameters are as follows:

Carrier Stop Time: Change from 5 bit times to 3 bit times (Section 13.2 of this document)
Carrier Decay Time: Change from 15 bit times to 6 bit times (Section 13.2 of this document)

Character Start/Stop requirements

Timing with respect to ‘characters’ was inadvertently omitted from Revision 8.0, but the Physical Layer can not allow unmodulated carrier or trailing ‘dribble’ bits/bytes. Therefore, the requirements of Physical Layer Specification Revision 7.2 must be reinstated as follows:

Time from RTS to first Character start bit: 5 bit times
Time from last Character to Carrier OFF: 11 bit times
(Carrier OFF: Carrier below maximum acceptable noise amplitude.)

Tests for Character Start/Stop timing are not included in this test procedure. Standard tests and methods for these parameters will be included in the next revision to this document. In the interim, however, device manufacturers should devise their own method of measuring these parameters for compliance with the above requirements.

Carrier Start/Stop Transients

'Carrier Start/Stop Transients' needs to be redefined as 'Carrier Transients'. Two problems were discovered after the initial release of Revision 2.1

1. The test filter requires AC coupling to prevent the filter from saturating.

2. The test specification and test plan do not specify or test for transients that occur during the entire transmission.

The entire procedure for Carrier Start/Stop Transients outlined in Section 13.3 of this document is in error and **should not be used**. In it's replacement, a complete updated procedure for Carrier Start/Stop Transients is contained as part of this errata, shown as Section 13.3A, and should be used until the Physical Layer test procedure can be revised in a future revision.

Proposed changes to the test plan are as follows:

13.3A Carrier Transient

When a HART device transmits, a transient spike should not be introduced into the network (see Figure 23. below). Large transients could interfere with the reception of HART signals by other devices or, more importantly, affect analog signaling. This test insures that transients remain within a range that does not interfere with analog signaling.

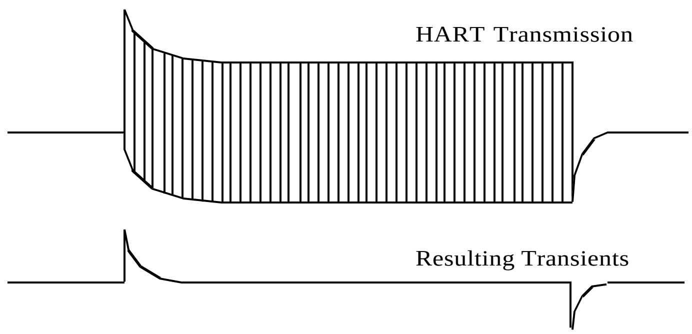

Figure 23. Carrier Start Transient

13.3.1A Requirements

The Physical Layer requires when passing a signaling waveform through the analog filter (see Section 10.8, Test Filters), carrier transients should decay quickly enough that filter output does not exceed 100 mV[1] above or below the DC average of the filter output for the duration of the carrier and for 50 ms after the carrier is turned off.

These requirements do not apply to the application or removal of a network connection (i.e., temporary connection of a secondary master).

13.3.2A Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. Load resistor 250 Ω (250 Ω used in place of test load test load specified in Table 1.)
2. 10 uF Tantalum Coupling Capacitor (25 V minimum)
3. Oscilloscope
4. PC and Software
5. DC Power Source
6. Analog Test Filter (HCF_TOOL-32)

1. Revision 8.1 Physical Layer Specification specifies 10mV, not taking into account the 10X filter gain.

13.3.3A Test Setup

Refer to Figure 3 through Figure 13 in Section 12 for device-specific test setups.

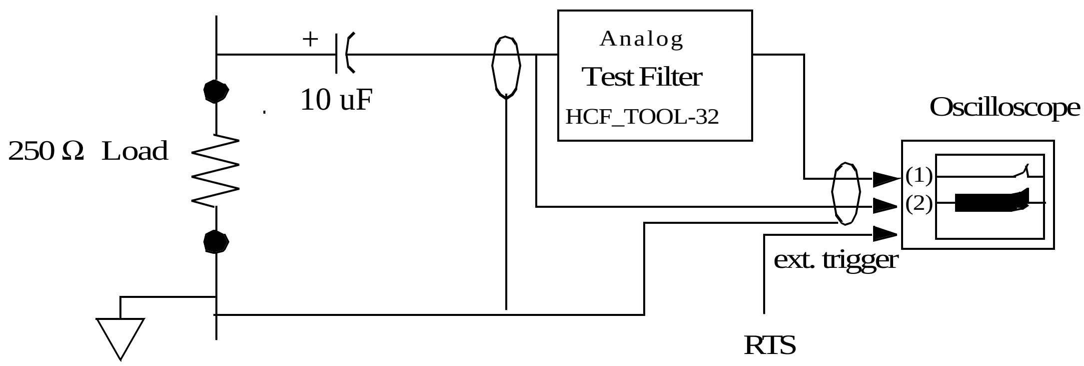

Figure 24. Carrier Transient Test Setup

13.3.4A Test Procedure

The transient characteristics are measured with an oscilloscope connected to the analog test filter as shown above. The test requires that measurement be performed for the duration of the carrier and for 50 ms after the carrier is turned off.

<u>Slave Device</u>

Using the HART master (PC and software) to assert a request to the slave test device. Connect an oscilloscope to the input and output of the Analog Test Filter and trigger with the RTS line of the Slave device modem circuit. Monitor the output of the test filter from the beginning through the end, and 50 ms beyond the end of the Slave device response.

<u>Master Device</u>

Use the HART master device under test to assert a request across the test load. Connect an oscilloscope to the input and output of the Analog Test Filter and trigger with the RTS line of the device modem circuit. Monitor the output of the test filter from the beginning through the end, and 50 ms beyond the end of the request message.

13.3.5A Notes on Carrier Transient

1. The RTS signal generated by the modem is used to trigger the scope. The trigger can be applied to the external trigger input or to a third input channel on the oscilloscope. Typically there is a DC offset between the modem and the analog current, therefore the probe connected to RTS must not have its ground connected to the modem's ground. The oscilloscope's trigger will need to be adjusted to compensate for the DC offset between the modem and the loop current. Use a positive trigger for end of carrier and a negative trigger for start of carrier.

2. Typically, a long stop transient is characteristic of excessive capacitance on the Output Transmit Analog circuitry.

3. The output of the test filter will normally show some effects due to the low frequency modulation of the FSK. These normal effects should be well within the test criteria.

4. This test MUST be done with a 250 Ω current sense resistor, which is different from all the other tests which a test load specified in Table 1.

13.3.6A Example Test Data

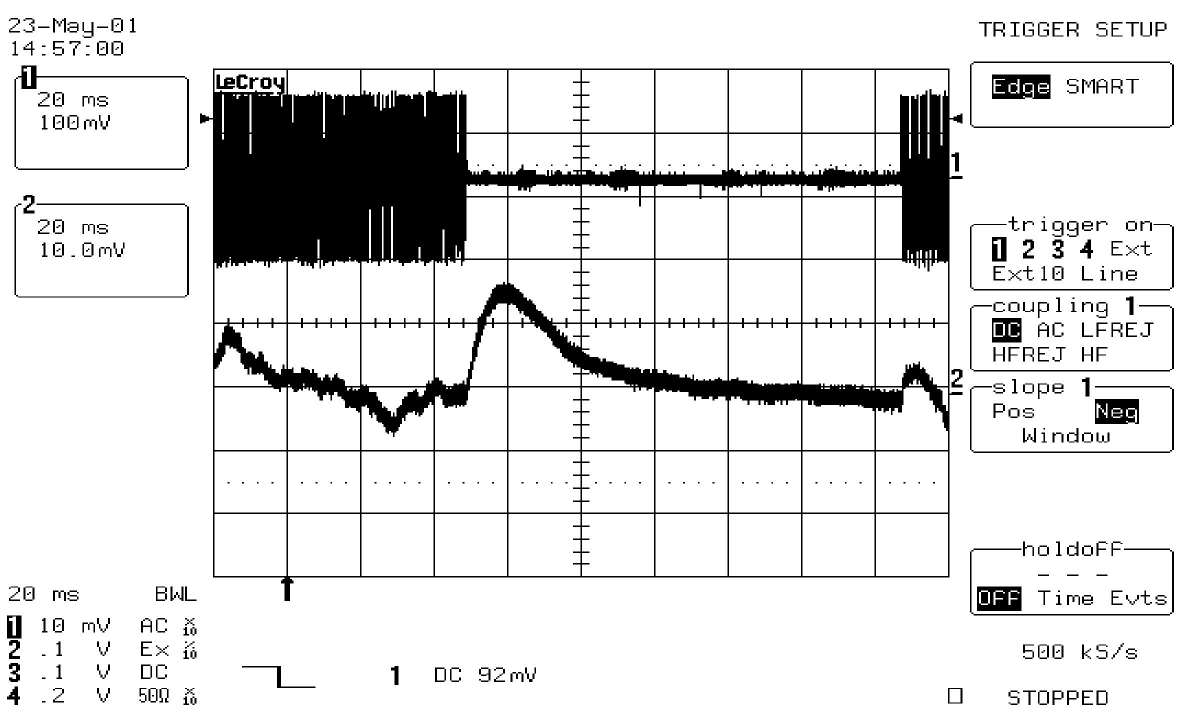

Figure 25. Sample #1 Waveform Carrier Transient

Waveform above shows peaks as high as 15 mV, well within the 100 mV criteria.

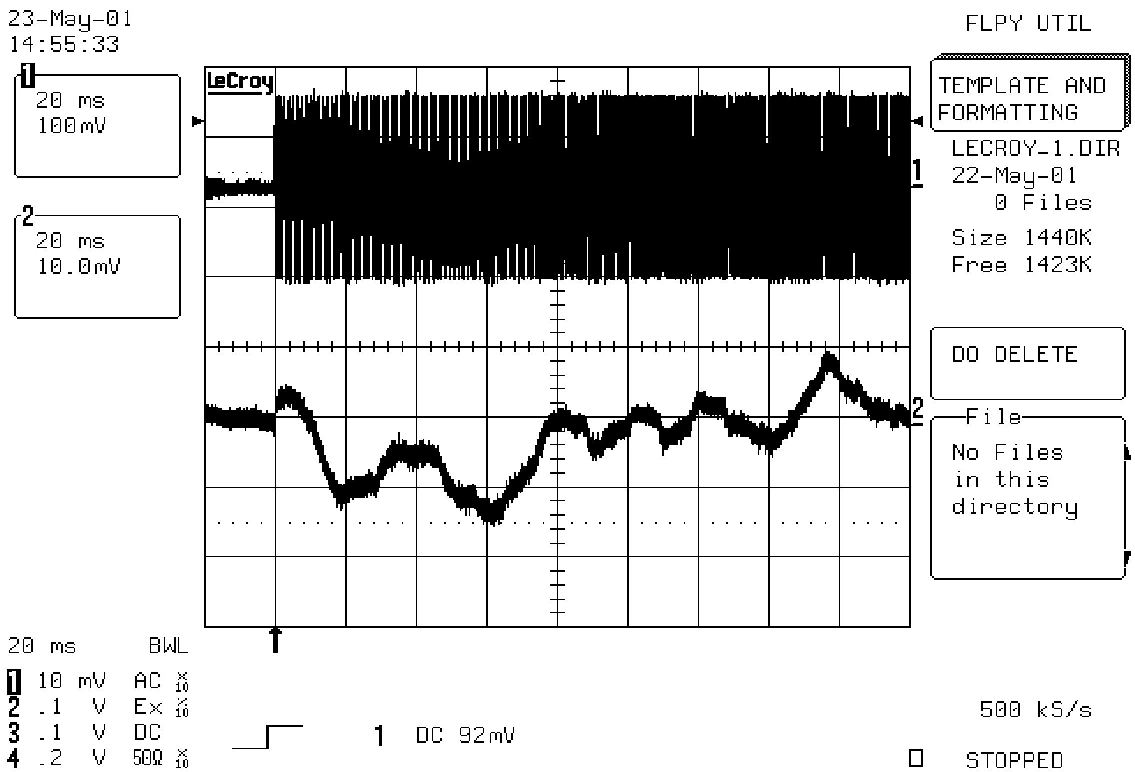

Figure 26. Sample #2 Waveform Carrier Transient

Waveform above shows a trailing transient of 15 mV, well within the 100 mV criteria.

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Preface

This version of the HART FSK Physical Layer Test Specification is intended for testing all device designs implemented to HART FSK Physical Layer Specification (HCF_SPEC-54). This revision of HCF_TEST-2 differs from the previous revision in the following ways:

- New test tools and test methods have been incorporated to simplify test procedures and improve consistency of results. The new test tools are available from the HART Communication Foundation as Physical Layer Test Kit (HCF_KIT-116).
- Test set ups and test procedures have been updated to reflect the requirements of HART FSK Physical Layer Specification Revision 8.1.
- Tests have been added for Carrier Decay and Delta Impedance.
- The document format was revised to more closely align with IEC/ISO specifications.

The HART Communication Foundation expresses its appreciation to the following individuals and their companies for contributions to the development of this specification:

NAME	**COMPANY**
Doug Arntson, Chairman, Editor	Rosemount Inc.
Robin Pramanik	Siemens AG
Stefan Probst	Endress & Hauser
Karl-Bernd Schaertner	Samson
Art Schrock	Endress & Hauser
Steve Seberger	Fisher Controls
Mark Sinreich	MACTek

Introduction

This specification defines the requirements for testing product designs for compliance with the HART FSK Physical Layer Specification. Consistent and conformant implementation of the HART Physical Layer is an important element to ensuring products of different manufacture will interoperate and communicate with one another on a HART network.

Product manufacturers are responsible to test and certify their products for conformance with the HART Protocol. This document and other elements of the HCF Quality Assurance Program are intended as tools to aid manufacturers in fulfilling that responsibility.

The protocol specifications take precedent over test specifications should any inconsistencies exist. Any discrepancies should be reported to the HART Communication Foundation.

1 SCOPE

The intent of the FSK Physical Layer Test Specification is to define conformance tests for HART devices so as to promote Physical Layer interoperability between devices. This document outlines all recommended tests, procedures and equipment necessary to determine conformance of all devices designed to the HART FSK Physical Layer Specification (see Section 2, Normative References).

HART compliance of the Physical Layer insures reliable communications on HART networks that may be constructed from devices of varying type and manufacture. Methods provided here allow a manufacturer to test their device for conformance over its operating limits. Deviation from HART conformance may negatively impact reliability of device communication.

2 NORMATIVE REFERENCES

2.1 Related HART Documents

1. HCF_SPEC-54, FSK Physical Layer Specification, Revision 8.1.
2. HCF_SPEC-54, FSK Physical Layer Specification, Revision 8.0.
3. HCF_SPEC-53, FSK Physical Layer Specification, Revision 7.2.
4. HCF_TEST-2, FSK Physical Layer Test Specification, Revision 1.0.
5. HCF_PROC-12, HCF Quality Assurance Program

3 DEFINITIONS

Analog Signaling	A low frequency signal (usually 4-20 mA) sent to or originating from a field device.
Analog Signaling Spectrum	The frequencies from DC to 25 Hz (with -40 dB per decade above 25 Hz).
Analog Test Filter	A low-pass filter (HCF_TOOL-32) designed to facilitate measurement of the amount of energy a digital signaling device may generate from assertion or removal of its carrier in the analog signaling spectrum.
Barrier	Intrinsically safe barrier. When both supply and return side barriers are used, the term ‘barrier’ also applies to the combination.
Current Sense Resistor	A resistor that may be used to convert analog current signal to a voltage signal.
Digital Signaling	Communication of information via the 1200 bps FSK HART signal.
Digital Signaling Spectrum	The frequencies from 500 Hz to 10 kHz (with -40 dB per decade below 500 Hz and -20 dB per decade above 10 kHz).
Digital Test Filter	A band-pass Filter (HCF_TOOL-31) is to facilitate measurement of the amount of energy an analog signaling device may generate in the digital signaling spectrum as well as the allowable noise imposed on the network during silence.
Extended Frequency Band	The range of frequencies from 500 Hz to 10 kHz that include the normal frequency band plus some guard band.
Field Device	A signaling element that usually resides in the process area and not in the control room. A field device may have any of the following properties: generate or receive an analog signal in addition to a digital signal; signal digitally by modulating current or voltage; loop powered or independently powered; source current, sink current, or be DC isolated from the loop.

Frame

The complete transmission of a given signaling element from start of carrier to end of carrier.

A frame consists of a preamble and message. Each frame is sent as a sequence of bytes using asynchronous character format. This format is most commonly used in data communication over voice-grade telephone lines. Each device signals in turn by applying its carrier to the medium for the full duration of its frame. Between frames there can be silence although a carrier detect transition may not actually occur (see Figure 27).

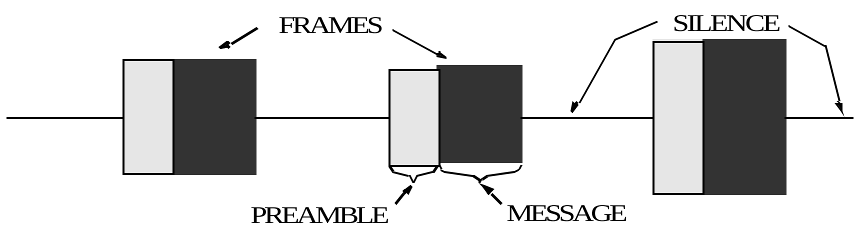


Figure 27. HART Digital Signaling Frames

The bit sequence within a character is one start bit (0), 8 data bits, one parity bit (odd), and one stop bit (1) as shown below in Figure 28. The parity will be true (1) if number of 1's in the data byte is even.

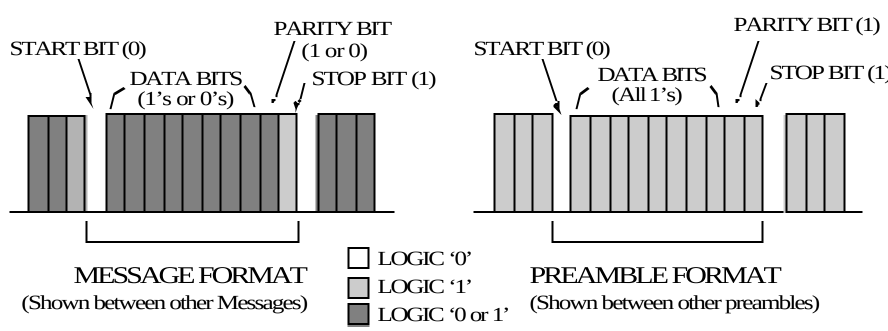


Figure 28. HART Byte Format

A thorough discussion of messages and the time between frames is given in the Data Link Layer Specification (HCF_SPEC-81).

Ground A connection to the surface of the earth or to conduits or pipes that are so connected, or to the safety bus bar or "0 volt rail" to which IS barriers are connected. Ground may or may not be the same as network power supply common.

Message The information-bearing part of a frame. Everything except the preamble part of the frame.

Network A single pair of cabled wires and the attached signaling and non-signaling elements. This definition also applies to single current loops. An installation using multiple-pair wire and a common network power supply is said to consist of multiple networks.

Network Power Supply A source that supplies operating power directly to a network.

Network Resistance The resistance or real part of the impedance of a network. Calculated as the parallel combination of the impedance of all parallel devices on the network. Usually dominated by one low impedance device.

Non-Signaling Element Any fundamental item of network hardware, such as a network power supply, that does not signal.

Normal Frequency Band The range of frequencies from 950 Hz to 2500 Hz used for digital signaling.

Preamble A sequence of hexadecimal FF characters preceding the message of each frame for the purpose of synchronization. Part of the message-detect pattern. The HART protocol requires a minimum of two (recommended 5) preambles.

PhL Test Interface HCF_Tool-35 used to perform physical layer testing.

Primary Master A Data Link Layer term for a signaling element that initiates communication with one or more slaves. This function is typically provided by the I/O card of a control system but could, theoretically, reside in any signaling element.

Secondary Master A Data Link Layer term for a signaling element that initiates communication with one or more slaves by means of an arbitration process defined in the Data Link Layer Specification.

Signaling Element	Any device that communicates digital information on a HART network by modulating current or voltage at its network terminals.
Silence	The state of a signaling element that is not transmitting or the state of the network when no carrier is present.
Slave	A Data Link Layer term for a device that responds to a primary or secondary master.
Turndown	Refers to the ability of some devices to be configured to respond to a smaller range of sensor output. Maximum turndown generally produces the maximum possible rate of change of the analog signal.

4 SYMBOLS AND ABBREVIATIONS

AWG	American Wire Gage
C_{tg}	Capacitance Terminal-to-Ground
C_{tt}	Capacitance Terminal-to-Terminal
C_X	Equivalent Device Capacitance
DUT	Device Under Test
FSK	Frequency Shift Keying
HART	Highway Addressable Remote Transducer
HCF	HART Communication Foundation
RMS	Root Mean Square
R_{tg}	Resistance Terminal-to-Ground
R_{tt}	Resistance Terminal-to-Terminal
R_X	Equivalent Device Resistance
RTS	Request to Send
UART	Universal Asynchronous Receiver Transmitter

5 TEST PROCEDURES

The HART Physical Layer can be tested using common lab equipment. Some tests require the use of tools available from the HART Communication Foundation or the construction of a simple test circuit. The tests are described based on the implementation of commercially available HART compatible modem integrated circuits. Test points are assumed to be accessible. Modification of the test circuit is also assumed possible.

6 TEST CONFIGURATIONS

Test configurations for all HART physical device types are described under appropriate headings later in this document. If a device can be characterized as more than one physical device type, all tests associated with each device type must be performed. Detailed descriptions of physical device types and characteristics can be found in the companion document, FSK Physical Layer Specification (see Section 2, Normative References).

All test procedures included in this specification assume the device under test (DUT) is powered and connected as an element in a HART network. The HART network may be as simple as a DC power source, a current sense resistor (test load) and one test device. Tests for HART masters typically use a network involving a test load connected across the master’s network terminals. Most tests are applied across the DUT.

7 TEST SUBSTITUTIONS

Tests are described for all types of HART devices. However, due to the complexity and uniqueness of some HART devices, it is possible that the test methods may not accurately test all intended electrical parameters. When necessary, a test method may be substituted with one that better quantifies the device’s Physical Layer parameters.

If a test is substituted, detailed test methods and all results must be documented along with the results of standard tests submitted to the HCF. The HCF reserves the right to dismiss substitute test results or methods deemed to inaccurately test Physical Layer parameters.

If a device was designed prior to revision 8.1 of the physical layer specification, the test methods and pass/fail criteria appropriate for the earlier specification may be substituted.

8 TEST CONDITIONS

All Physical Layer tests must be performed under the following minimum conditions:

1. Ambient room temperature
2. Loop current: 4 mA (For 4-20 mA devices unless otherwise noted)
3. Wiring: 22 AWG min size, less than 1 meter lengths.
4. Grounding: Chassis ground of all equipment connected to earth and one connection that references the test circuit to ground, unless otherwise stated. Since the Physical Layer Specification does not dictate the grounding schemes to be employed by various types of devices, it is impractical for this document to specify all appropriate ground connections for use in testing. Therefore, the test engineer should determine an appropriate grounding scheme for each test. Inappropriate grounding will generally cause problems rather than mask them.

   Some test methods for devices that are normally ground isolated specify certain abnormal chassis ground connections to facilitate worst-case impedance measurement (see Section 13.7.3, Send Impedance Test Setup).

The device manufacturer is responsible to set up test conditions adequately representing all conditions under which the product may be used. For example, if a device has physical layer properties that vary with loop current or ambient temperature, the device should be tested at the operating extremes of these conditions.

9 TEST RESULTS

Device performance under all rated operating conditions is the responsibility of the manufacturer. The tests described in this specification are intended to aid manufacturers in the determination of a device's capabilities and limitations in a variety of possible applications. Every HART communicating device should be tested for conformance to the HART Protocol Specifications.

Manufacturers of devices satisfying requirements of the HART Protocol Specifications may register a statement of conformance and test results in accordance with the HCF Quality Assurance Program, HCF_PROC-12.

10 PHYSICAL LAYER TEST EQUIPMENT

The following list of equipment is necessary to conduct Physical Layer testing.

10.1 Test Load Resistor Properties

Requirements for the Test Load Resistor vary according to the impedance of the device under test.

Table 1. Test Load Resistor Properties

Physical Device Type (Note 1)	Test Load Resistance	Parasitic Capacitance	Inherent Inductance
Low Impedance	1000 Ω ± 1%	5 pF max.	1 μH max.
High Impedance	500 Ω ± 1%	5 pF max.	1 μH max.

Note 1: Refer to Section 11 for a description of physical device types and their associated impedance.

10.2 Oscilloscope

Minimum requirements:

1. Dual trace.
2. 20 MHz.
3. External trigger.
4. Method of recording waveform: camera, plotter, or computer interface.
5. Delayed trigger.
6. Roll mode time base (recommended to monitor HART communications).

An oscilloscope with storage capability is preferred. The scope is used for voltage measurements that verify calibration. Scope readings should attain a nominal accuracy of 5% to be considered sufficient for testing purposes.

10.3 Frequency counter

HP5316B or equivalent counter capable of measuring 1200 and 2200 Hz within 0.1%.

10.4 DC Power Source

The power supply must be:

1. Capable of at least 10V beyond the voltage range of the DUT. Generally, 40V will suffice.
2. Capable of at least 8 mA beyond the current range of the DUT. Generally, 50mA will suffice.
3. The power supply should have a low output impedance and low output noise. A poor quality power supply will not invalidate a test but may contribute to test failure.

For the Noise Sensitivity test, a power supply capable of modulating it's output in response to an input from a signal generator is required. The power supply should also be capable of both sinking and sourcing current. If it is not capable of sinking current, a load resistance may be connected across the power supply's output such that it is always sourcing current, even if the test setup does not require it.

For the Output Noise During Silence test, a battery source should be used to power the test device to reduce the noise emitted from a noisy power source.

10.5 PC and Software

A personal computer (PC) with software capable of emulating certain specific functions of a HART master and/or HART slave is required for some tests. The software is available from the HART Communication Foundation as HCF_TOOL-39 (XMTR) and HCF_TOOL-25 (COMTEST). HCF_TOOL-25 is used when the DUT is a Slave. HCF_TOOL-39 is used when the DUT is a Master.

10.6 PhL Test Interface

The PhL Test Interface (HCF_TOOL-35) is the required PC interface for Physical Layer testing. The output amplitude of the PhL Test Interface is adjustable. It provides a suitable PC interface for all Physical Layer testing, however, the proper transmit amplitude must be verified before conducting each test. The PhL Test Interface is available in the HCF-KIT-116.

10.7 High Impedance Current Source

Low Impedance Device tests require use of a high impedance current source. A transmitter or DC-isolated bus device with impedance greater than 100 kΩ in the Normal Frequency Band of 500 Hz to 10 kHz can be used in this capacity.

10.8 Test Filters

1. Digital Filter, HCF_TOOL-31[1].
   A Butterworth type bandpass filter with a pass band of 500 Hz to 10 kHz, 2nd order roll-off below 500 Hz, and 1st order roll-off above 10 kHz. The test filter has a gain of 10X which the test data sheets take into account in the test criteria. The Digital Test Filter is available in the HCF-KIT-116.

2. Analog Filter, HCF_TOOL-32[1].
   A Butterworth type lowpass filter with a pass band of 0 - 25 Hz and 2nd order roll-off above 25 Hz. The test filter has a gain of 10X which the test data sheets take into account in the test criteria. The Analog Test Filter is available in the HCF-KIT-116.

10.9 RMS Digital Volt Meter (DVM)

Differential True RMS Voltmeter, Fluke model 8840A or equivalent. Not suitable for all tests due to limited bandwidth, in which case an oscilloscope should be used.

10.10 Signal Generator

The requirements of the signal generator depend partly on modulation capabilities of the power supply. If the power supply does not have modulation capabilities, the signal generator must be connected in series with the power supply to produce the required signals. If the power supply has modulation capability, the signal generator requirements may be different.

The combination of signal generator and power supply must be capable of generating the signals specified in Table 15, Noise Sensitivity Levels, at the terminals of the DUT. If the DUT is a high impedance device, a small margin above these levels will be adequate. If the DUT is a low impedance device, the levels at the output of the Power Supply/Signal Generator may need to be substantially larger than the table specifies to produce those levels at the DUT terminals. Experimentation may be required to determine the appropriate signal levels at the power supply.

10.11 AC Ammeter

An AC Ammeter is required for the 25 Hz analog signaling interference test on Low-Impedance devices. It shall be capable of measuring the peak-to-peak current (may be calculated from RMS) variation at 25 Hz and 16 mA (ignoring the DC DUT operating current).

1. Available from the HCF.

11 PHYSICAL DEVICE TYPES

The primary distinction between devices is impedance level. All signaling elements can be classified as either low impedance or high impedance devices (see Table 2, Table 3, and Table 4 below). Further distinctions are made on the basis of connection type. Physical device types are listed in the table below. If a device exhibits characteristics of more than one physical device type depending on its implementation in the field, all Physical Layer tests for each device type should be performed.

For maximum compatibility with preexisting equipment, low impedance devices must have an impedance of 230 Ω - 600 Ω within the normal frequency band (950 Hz - 2500 Hz). Detailed descriptions of physical device types and connection types can be found in the companion document, FSK Physical Layer Specification (see Section 2, Normative References).

Table 2. High Impedance Devices

Connection Type	Characteristics	Examples
Current Output	1. Provides analog signal to the loop 2. Usually not isolated from ground	The controller connection for an analog output loop (a loop with a common 4-20 mA actuator or positioner as the field device). A separately-powered field device sourcing current to the loop rather than sinking it from the loop.
Voltage Input	1. Does not provide DC power to the loop 2. May or may not be isolated from ground	The controller connection for an analog input loop where the analog signal is voltage (e.g., from a voltage output transmitter). A separately powered output device that accepts voltage as its analog input signal rather than current.
Secondary	1. DC isolated from the current loop 2. Not included in wire length calculations 3. Not required for communication on the loop	Any device intended as a removable connection, such as a handheld terminal or other type of temporary connection.
Transmitter	1. Draws DC current from the loop 2. DC isolated from ground 3. Varies amount of current drawn as a means of analog signaling	A 2-wire transmitter. A separately powered transmitter with loop interface that draws DC from the loop.

Table 3. Typically High Impedance Devices

Connection Type	Characteristics	Examples
Non-DC Isolated Bus Device	1. Usually draws a constant DC current from the loop but not required to derive power from the loop. 2. Usually DC isolated from ground.	A 2-wire transmitter in a fixed current mode.
DC Isolated Bus Device	1. Does not affect analog signaling. 2. Entirely DC isolated. 3. May reside on any loop.	An independently-powered device connected to the loop for digital communication only.

Table 4. Low Impedance Devices

Connection Type	Characteristics	Examples
Current Input	1. Usually not isolated from ground 2. Assumed to have an integral current sense impedance (usually a 250 Ω resistor).	The controller connection for an analog input loop (a loop with a common 4-20 mA transmitter as the field device).
Voltage Output	1. Does not provide DC power to the loop. 2. May or may not be isolated from ground.	A 3-wire voltage output transmitter. A controller designed to send an analog signal to a separately powered field device.
Actuator	1. Draws DC from the loop at a current determined by the sourcing device. 2. DC isolated from ground.	A 2-wire device that receives analog signal via the 4-20 mA loop current supplied by a controller.

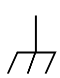
All network devices (with the exception of some non-communicating devices) must be described and specified according to their connection to both wires of the loop. Every device instruction manual is expected to identify the connection types for which the device can be configured. For each connection type, manuals should also detail the characteristics and parameters listed in Table 5 below.

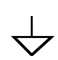
Table 5. Device Connection Characteristics

Characteristic	Parameters
DC isolated from ground	Minimum R_{tt} and maximum C_{tt} under worst-case conditions of an unbalanced network.
Not DC isolated from ground	Minimum R_{tt} and maximum C_{tt} as normally connected and a description of the ground reference.
Device draws DC from loop:	The amount of current drawn and the minimum terminal voltage at which communication is physically possible.
Device sources DC to loop	The limitations on sourced current and voltage and the maximum load voltage at which communication is physically possible.
Device signals with analog current	Current limitations and terminal voltage requirements.
Low impedance devices	Both minimum and maximum impedance magnitudes in the HART normal frequency band (950 Hz - 2500 Hz).

12 DEVICE TEST SETUP

Diagrams in this section demonstrate the setup of each device connection type for Physical Layer testing. Many of these diagrams will be referenced in the test procedures that follow. Test setups should be implemented as described unless otherwise noted in the test description. Each diagram includes the following symbols:

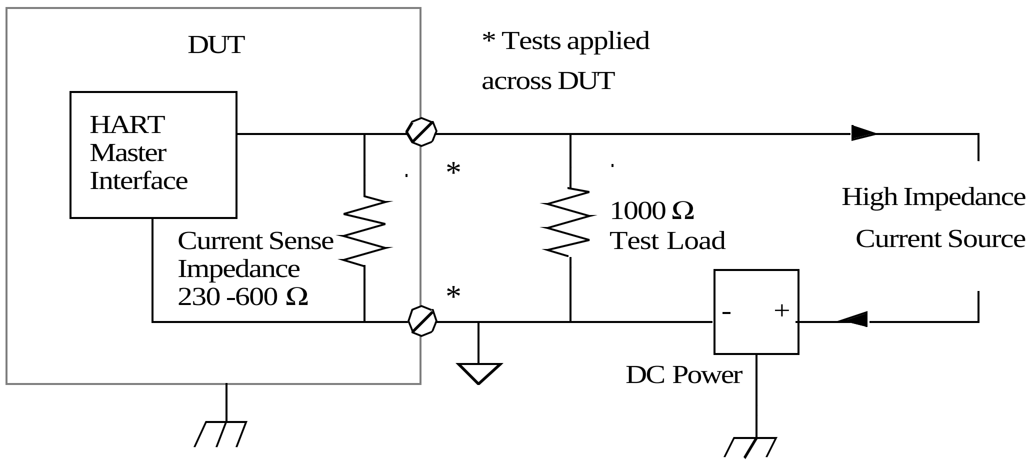
 = Chassis Ground

 = Signal Ground

In most cases, tests are asserted across the DUT. Other signals associated with the HART modem chip in the DUT may also be required to perform the testing. If a device is capable of behaving as more than one device connection type, it must be tested to the specification for each applicable physical device type.

12.1 Current Input Device Test Setup

A typical Current Input Device is an input channel of a control system (DCS, PLC, other) that receives the 4-20mA signal from a Transmitter.



Note: DC Power in some cases may be an integral component of a Current Input

Figure 29. Test Setup for Current Input Device

12.2 Current Output Device Test Setup

A typical Current Output Device is an output channel of a control system (DCS, PLC, or other) that sends (modulates) the 4-20mA to a field control device such as an Acutator. In addition, another Current Output Device is a 4-wire Transmitter that sources current.

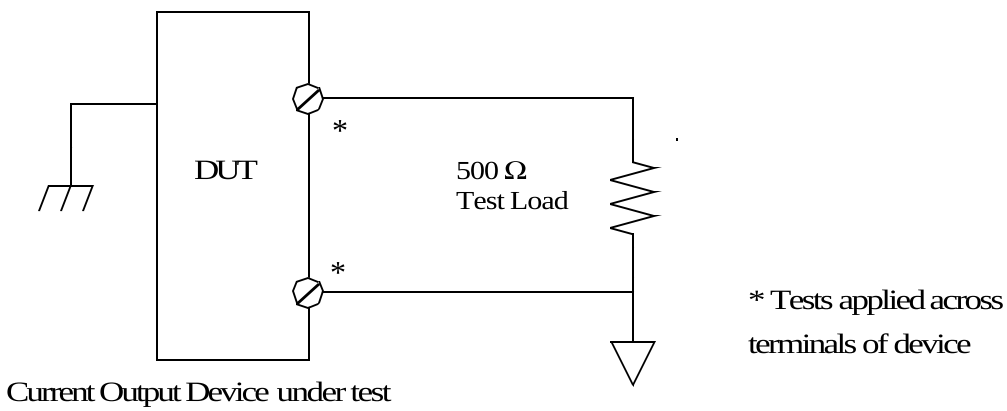


Figure 30. Test Setup for Current Output Device

12.3 Voltage Input Device Test Setup

A typical Voltage Input Device is an input channel of a control system (DCS, PLC, or other) that receives (measures) DC voltage from a Voltage Output Device.

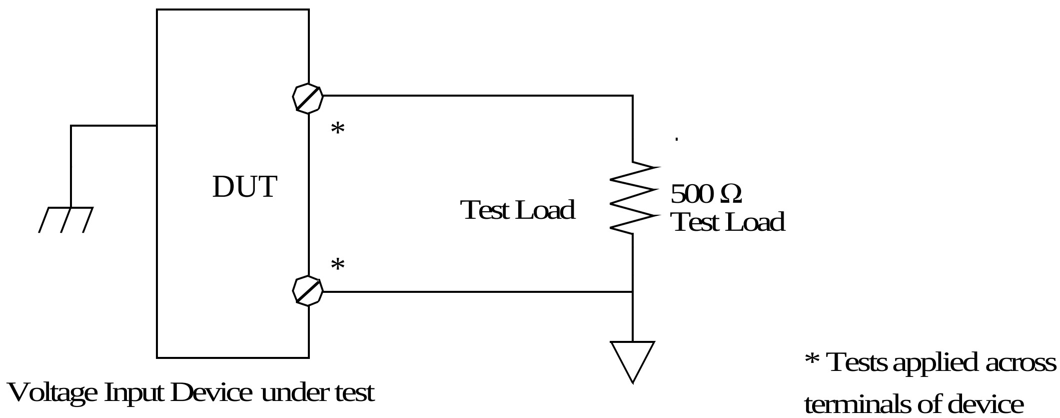


Figure 31. Test Setup for Voltage Input Device

12.4 Voltage Output Device Test Setup

A typical Voltage Output Device is a 3 wire device that derives its power from an external source. It signals by varying its DC output voltage (for example: 1 - 5 VDC) while superimposing HART voltage signaling.

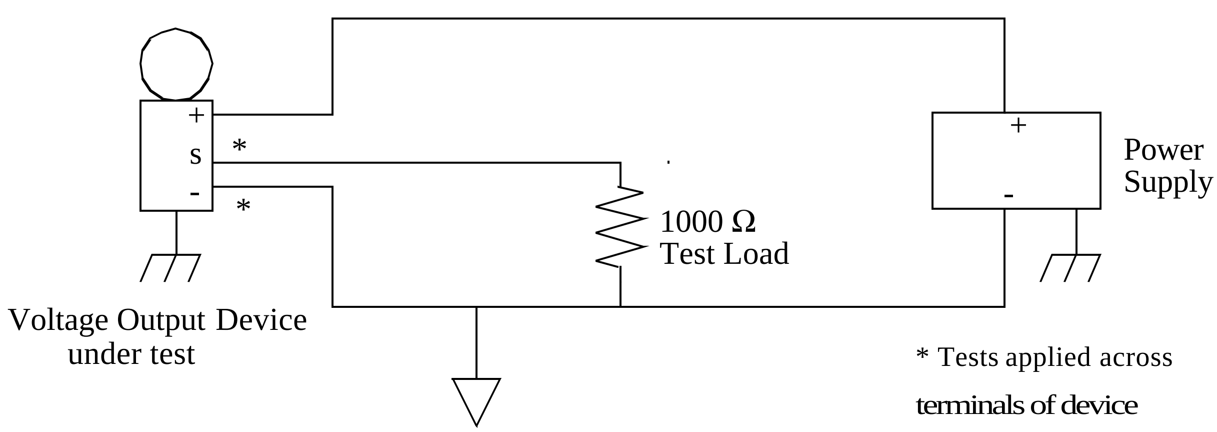


Figure 32. Test Setup for Voltage Output Device

12.5 Secondary Device Test Setup

Typically, a Secondary Device connects across an existing current sense resistor and functions as a Secondary Master. Although a Secondary Master can permanently reside on a HART network, in many cases the connection is temporary.

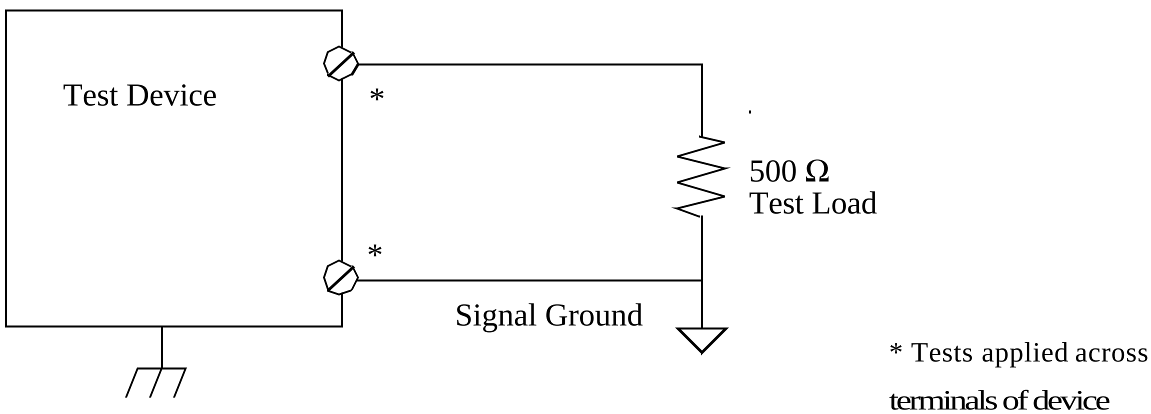


Figure 33. Test Setup for Secondary Devices

12.6 Transmitter Device Test Setup

A 2-wire Transmitter Device is powered from the loop connection, whereas 3-wire and 4-wire Transmitter Devices are not powered by the loop nor do they source current. A Transmitter device signals by modulating its output current (typically 4-20 mA).

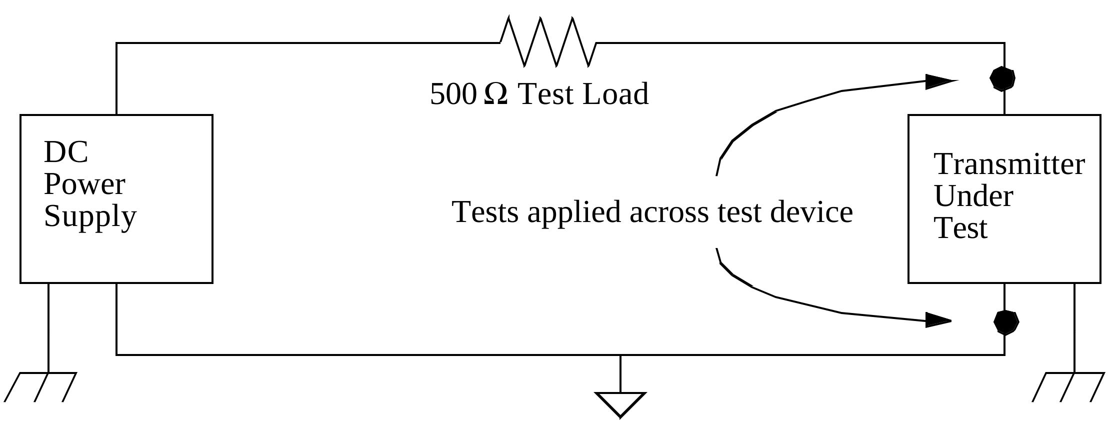


Figure 34. Test Setup for 2-wire Transmitter Devices

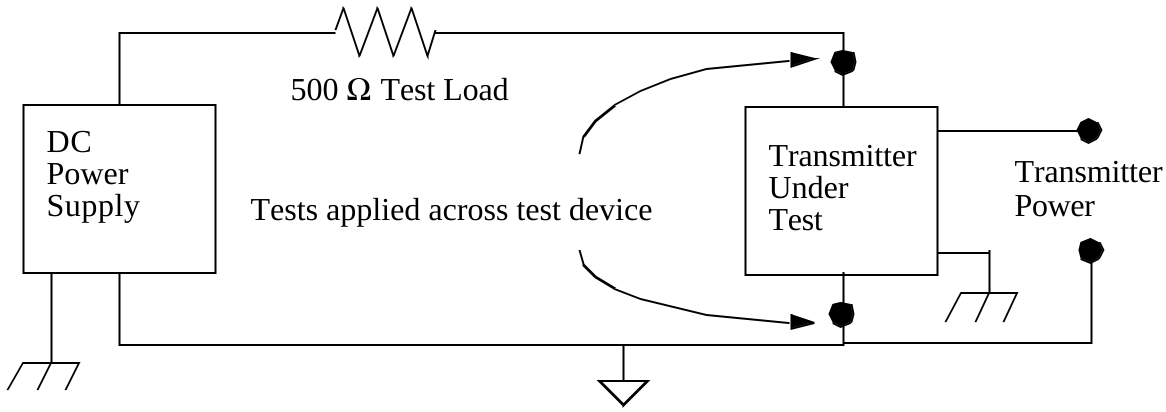
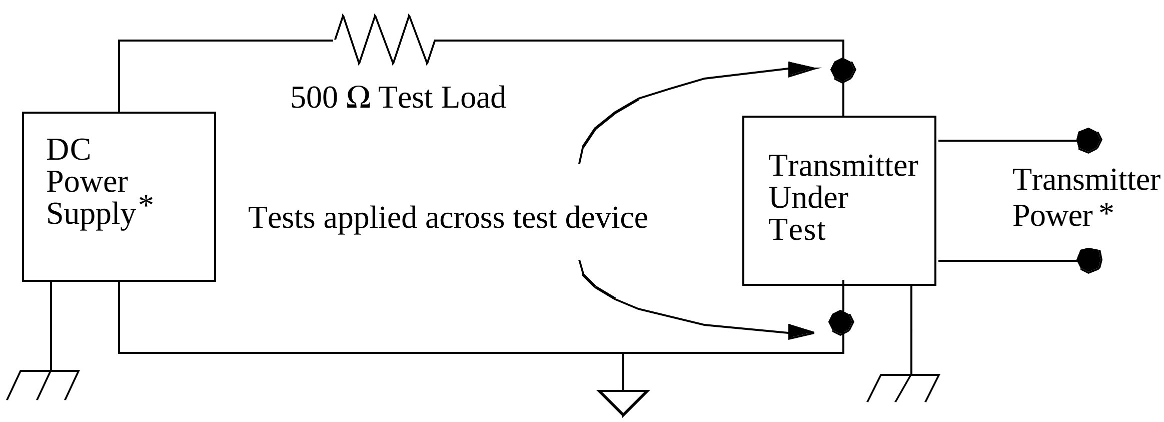


Figure 35. Test Setup for 3-wire Transmitter Devices



* Note: Transmitter power must be isolated from DC Power Supply

Note: A 4 wire device that sources current is considered a Current Output Device

Figure 36. Test Setup for 4-wire Transmitter Devices

12.7 Actuator Device Test Setup

An Actuator Device typically derives its power from the loop connection. It signals by modulating a voltage across its terminals.

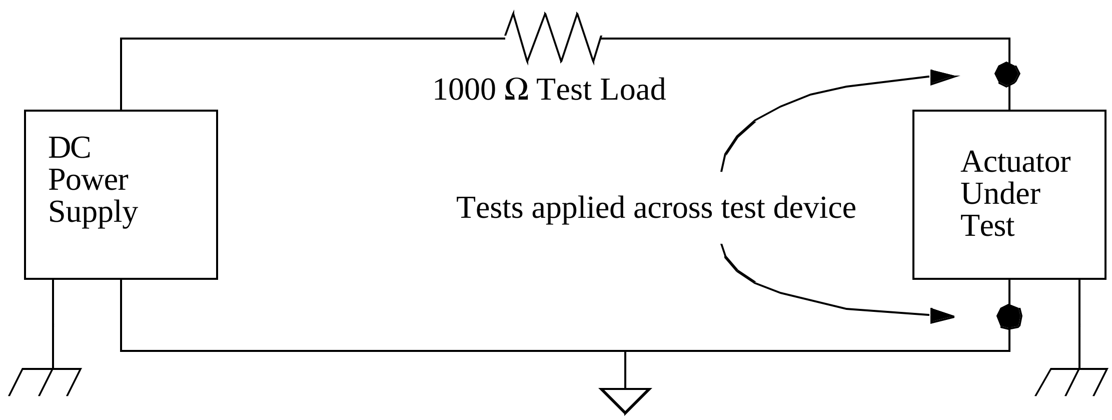


Figure 37. Test Setup for Actuator Device

12.8 Non-DC Isolated Bus Device Test Setup

A typical Non-DC Isolated Bus Device is a loop powered (2 wire) Transmitter operating under normal conditions with its current fixed (typically at 4 mA).

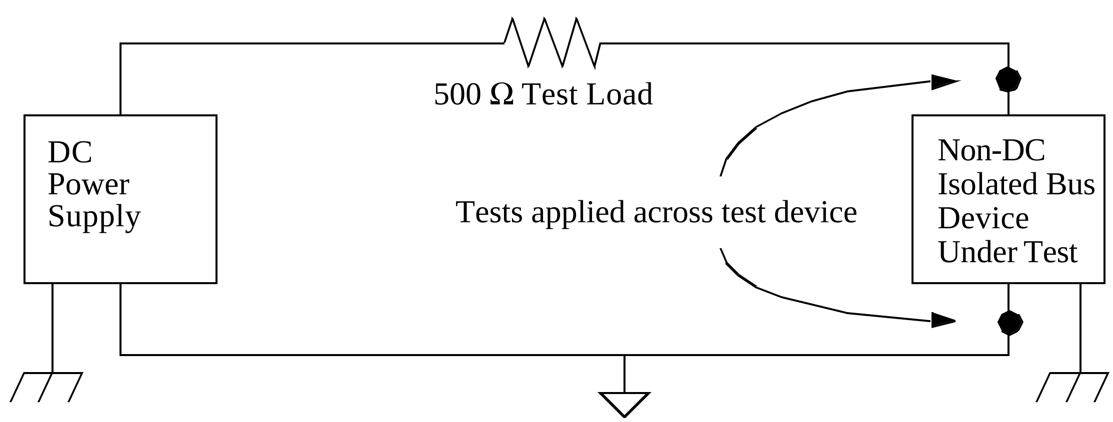


Figure 38. Test Setup for Non-DC Isolated Device

12.9 DC Isolated Bus Device Test Setup

A DC Isolated Bus Device is an independently-powered device that connects to the loop for digital communication only and does not affect the DC current in the loop.

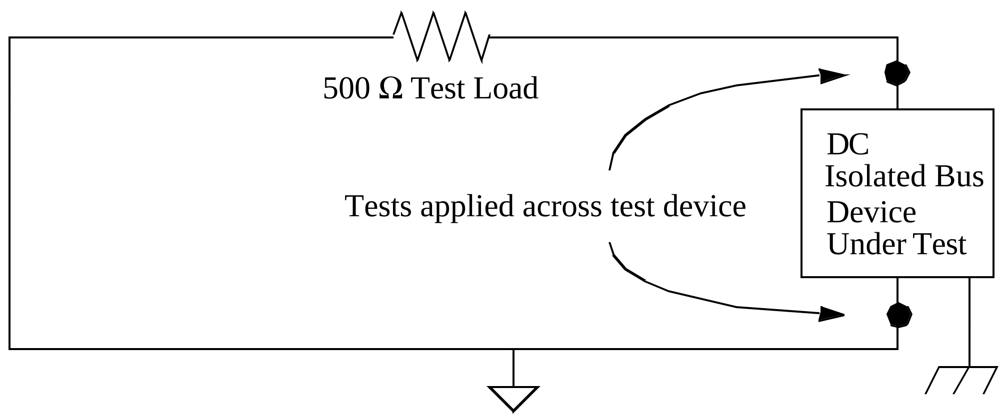


Figure 39. Test Setup for DC Isolated Device

13 PHYSICAL LAYER TESTS

Each test in this section includes the parameters to be tested, a list of equipment required to conduct the test, the requirements for compliance to the HART Physical Layer Specification, and sample test data. Some tests include sample procedures, as well.

A complete list of the required tests for HART compliance relative to the Physical Device Type is shown below in Table 6. Not all tests are required for each device. The tester should be certain which physical device type(s)[2] categorize the DUT and be familiar with the appropriate setup(s) for each type. For information about physical device types and setup procedures, refer to Section 11, Physical Device Types, and Section 12, Device Test Setup.

Table 6. Required tests relative to the Physical Device Type

	Current Output	Voltage Input	Secondary	Transmitter	Non-DC Isolated Bus	DC Isolated Bus	Current Input	Voltage Output	Actuator
Waveshape	X	X	X	X	X	X	X	X	X
Carrier Start / Stop / Decay	X	X	X	X	X	X	X	X	X
Start/Stop Transient	X	X	X	X	X	X	X	X	X
Output Noise During Silence	X	X	X	X	X	X	X	X	X
Analog Rate of Change	X			X					
Receive Impedance Measurement	X	X	X	X	X	X	X	X	X
Send Impedance Measurement			X				X	X	X
Noise Sensitivity	X	X	X	X	X	X	X	X	X
Carrier Detect Level	X	X	X	X	X	X	X	X	X
Carrier Detect Start/Stop	X	X	X	X	X	X	X	X	X

2. It is possible for a device to have the physical characteristics of more than one type

13.1 Waveshape

In testing for compliance of the transmitted HART waveform, three parameters are measured.

1. *Signal Amplitude*
   The amplitude of a signal applied to the network should be large enough that a receiving device can detect it. Conversely, a signal too large may cause inadvertent crosstalk on adjacent wiring.

2. *Signal Waveshape*
   Waveshape characteristics limit the magnitude of high frequency components in a transmitted signal. The higher frequency components can be coupled into other networks causing interference.

3. *Transmit Frequency*
   A receiving modem expects HART data to be transmitted at1200 bits/s and for the modulation frequencies to be 1200 and 2200 Hz. Typically, the baud rate and the modulation frequencies are determined by the oscillator(s) clocking the microprocessor and modem circuits.

13.1.1 Requirements

The transmit waveform must meet the frequency, amplitude and shape requirements shown in Figures 40a and 40b, Table 7, and Table 8 below:

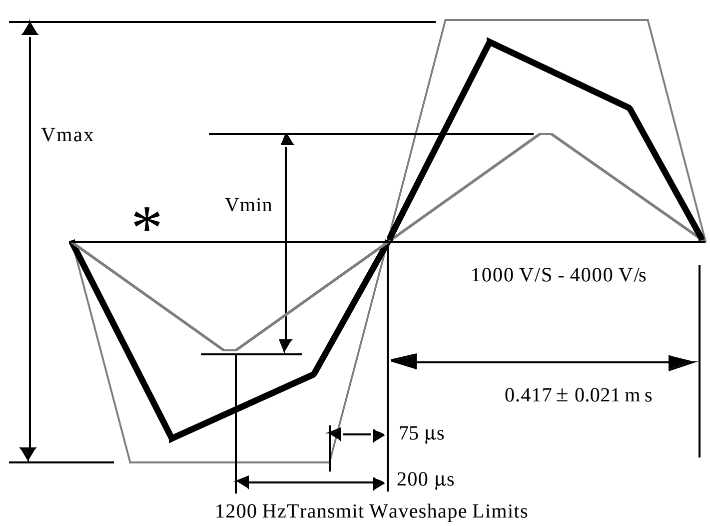


Figure 40a. Waveform Waveshape Requirements

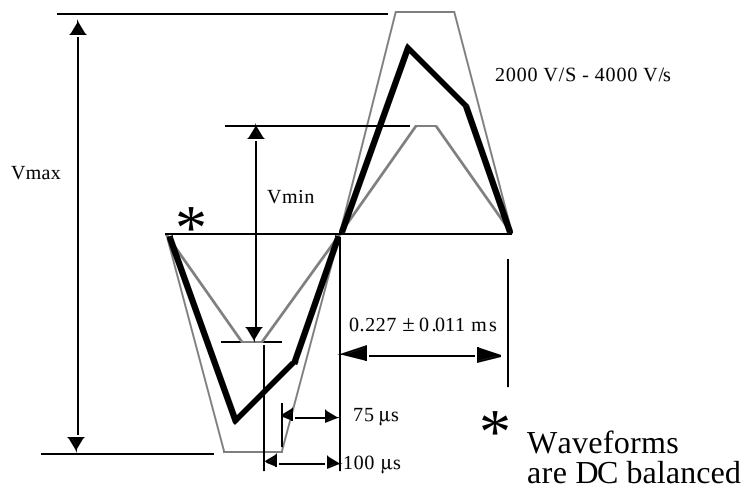


Figure 40b. Waveform Waveshape Requirements

Table 7. Signal Timing

Parameters	Limits
Bit Rate (bps)	1200 ± 1%
Mark (logic 1) frequency	1200 Hz ± 1%
Space (logic 0) frequency	2200 Hz ± 1%

Table 8. Waveform Amplitude Requirements

Physical Device Type	$V_{min.}$ (Minimum Amplitude)	$V_{max.}$ (Maximum Amplitude)	Test Load
Low Impedance	400 mVpp	800 mVpp	1000 Ω ± 1%
High Impedance	400 mVpp	600 mVpp (Note 1)	500 Ω ± 1%

Note 1: Allowable to be 800 mVpp into test load if it is ≤ 800 mVpp into 1 kΩ test load.

13.1.2 Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. Test Load Resistor (refer to Table 1)
2. Oscilloscope
3. Frequency Counter
4. DC Power Source

13.1.3 Test Setup

The waveshape test should generally be configured as shown in Figure 41 below. Refer to Figures 29 through 39 in Section 12 for device-specific test setups.

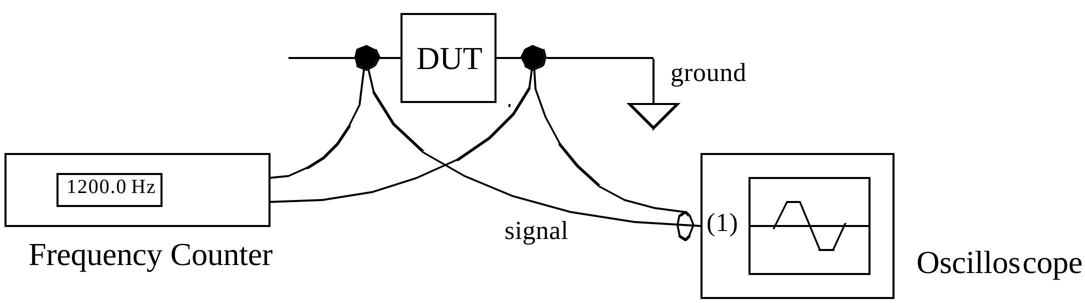


Figure 41. Waveshape Test Setup

13.1.4 Test Procedure

Waveform characteristics for the 1200 and 2200 Hz HART signalling are measured with an oscilloscope and a frequency counter connected according to the test set-up.

1. Use an oscilloscope to capture and record the 1200 and 2200 HART signals using one of the three methods outlined below.

   A. Configure the DUT's modem into a test mode (as in the example below) by sourcing steady state signals.

      Example Procedure:

      Connect the modem's RTS (Request To Send) pin to VSS (Ground) and the TXD (Transmit Digital) pin to VDD (Power). The modem should transmit a constant 1200 Hz signal. Measure and record the transmit frequency with a frequency counter. The waveform characteristics can be measured with an oscilloscope. Repeat the above steps with TXD connected to VSS for a constant 2200 Hz signal.

B. Create special DUT software to output successive 1200 Hz and 2200 Hz signals.

C. Record commands/responses from real messages by capturing at least three repetitive1200 Hz and 2200 Hz signals.

This method is not recommended because of the difficulty of obtaining an accurate frequency measurement. A frequency counter typically requires a repetitive signal. An oscilloscope's time base is not usually precise enough to measure frequency.

2. Measure and record the value of the current sense resistor. The amplitude of a current signaling device depends on the actual value of sense resistance.

13.1.5 Notes on Waveshape

1. When capturing a waveform with an oscilloscope, the tester should try to get only one complete waveform cycle using as much of the vertical and horizontal area as possible to maximize resolution. Averaging the waveform with the oscilloscope is not allowed.
2. Current input and Secondary devices having a selectable current sense resistor are required to meet the specifications with any allowed value. Separate tests with the minimum and maximum allowed values should be conducted.
3. For those devices that signal with current, the impedance of the power supply will be in series with the impedance of the test load. The larger impedance will increase the measured amplitude. Typically this will not cause any significant problems, since most power supplies have a very low internal impedance. It is permissible to measure the waveform across the test load using a differential or isolated oscilloscope.

13.1.6 Example Test Data

The following is an example waveform for a HART conformant device at 1200 Hz.

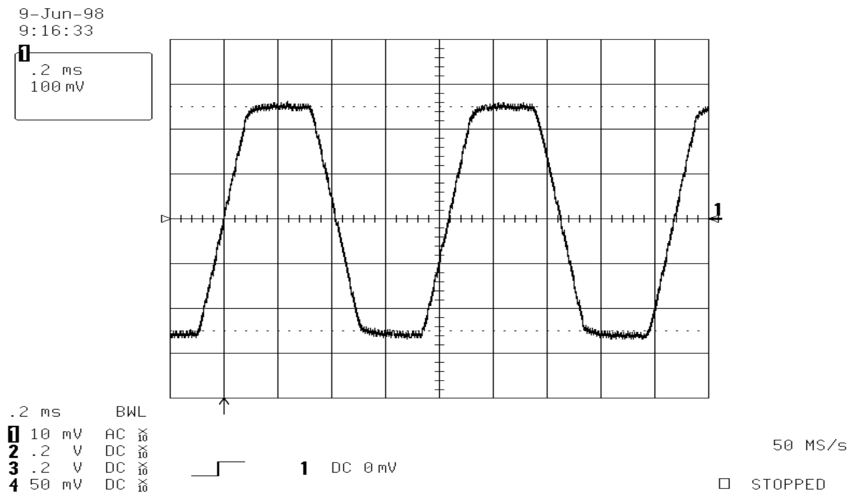


Figure 42. Sample Waveform at 1200 Hz

The following is an example waveform for a HART conformant device at 2200 Hz.

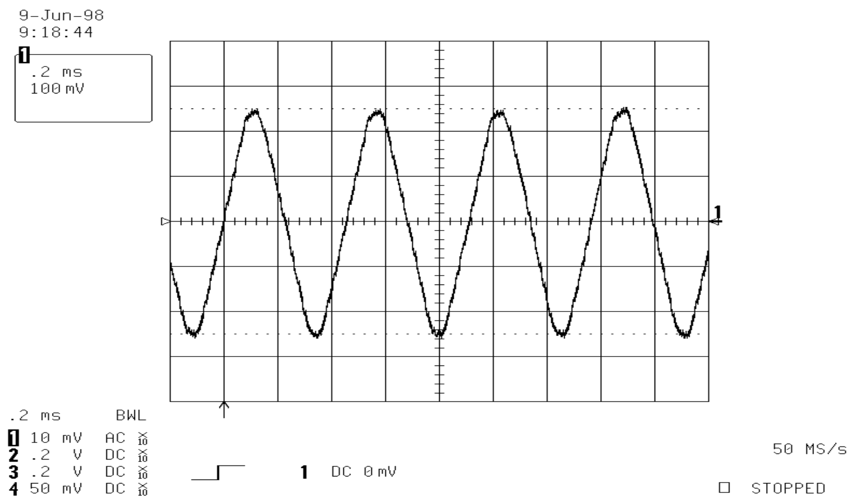


Figure 43. Sample Waveform at 2200 Hz

13.2 Carrier Start/Stop/Decay Timing

Carrier timing is tested to insure the transmitted signal level has an appropriate rise or fall time at the start and finish of each transmission. Compliance of carrier timing requires that three parameters are measured:

1. *Carrier Start*
   Time from the assertion of RTS until the carrier reaches the maximum receive threshold amplitude (120 mVpp). A device signal must be applied to a HART network within this time frame for proper bus arbitration to occur.

2. *Carrier Stop*
   Time from the disassertion of RTS until the carrier drops to below the minimum receive amplitude (80 mVpp). A carrier must diminish quickly enough when removed from the network in order to allow other devices access to the network and to avoid corruption of analog signaling due to long decay times.

3. *Carrier Decay*
   Time from the disassertion of RTS until the carrier drops to an amplitude within the range of allowable noise. A carrier must diminish quickly enough when removed from the network in order to allow other devices access to the network and to avoid corruption of analog signaling due to long decay times.

13.2.1 Requirements

1. *Carrier Start*
   The maximum allowable time for carrier signal to reach a minimum acceptable amplitude of 120 mVpp is 5 bit times, or 4.2 ms, as shown in Figure 44.

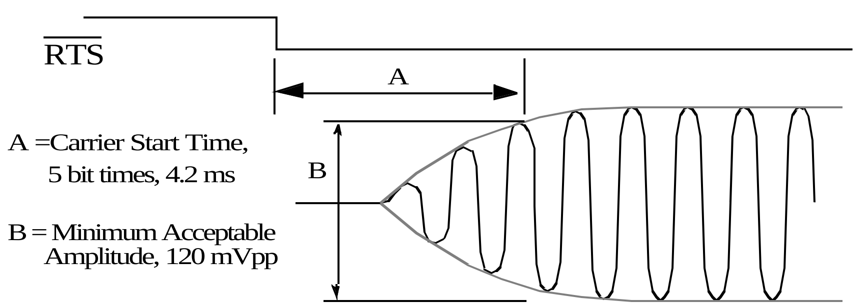
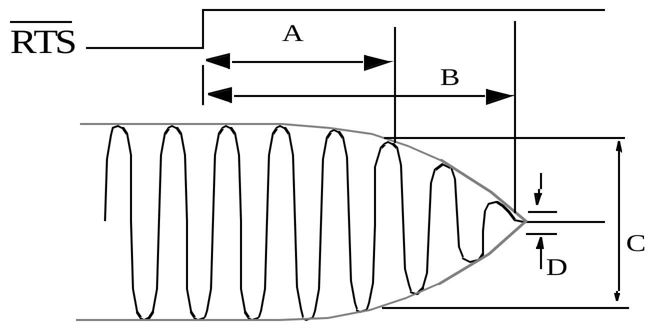


Figure 44. Start of Carrier

2. *Carrier Stop*
   The time at which the carrier first drops below 80 mVpp and does not again exceed 80 mVpp is illustrated below in Figure 45.



A = Carrier Stop Time, 2.5 ms
B = Carrier Decay Time, 5 ms
C = Minimum Acceptable Amplitude (Carrier Stop), 80 mVpp
D = Maximum Noise Amplitude (Carrier Decay), 2.2 mVRMS (6.16 mVpp)

Figure 45. End of Carrier

3. *Carrier Decay*
   Figure 45 above illustrates the time at which the carrier first drops below the maximum allowable noise amplitude of 6.16 mVpp.

13.2.2 Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. Test Load Resistor (see Table 1 on page28)
2. Oscilloscope
3. DC Power Source
4. PC and Software
5. PhL Test Interface

13.2.3 Test Setup

The Carrier Start/Stop/Decay characteristics are measured with an oscilloscope connected across the DUT as shown in Figure 46. Refer to Figures 29 through 39 in 12, Device Test Setup, for device-specific test setups.

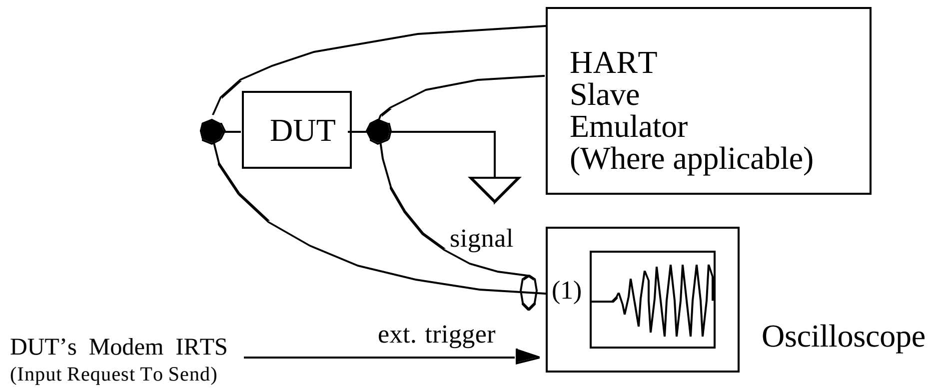


Figure 46. Carrier Start/Stop/Decay Test Setup

13.2.4 Test Procedure

When testing a slave, a repetitive command is issued from a HART master (PC and software) to initiate a reply that can be observed. When testing a master, only the request is observed.

In order to view the start or the stop of the carrier, the oscilloscope should be triggered from the RTS (Request To Send) signal at the modem. For loop powered devices, caution must be used in grounding, since the test device ground is often isolated from the current sense resistor.

<u>Carrier Start</u>

1. Connect one channel of the scope across the DUT.
2. Connect the second channel to the IRTS pin of the HART modem and use the negative edge as the trigger to the sweep.
3. Adjust the output of the unit under test to mid-scale output.
4. Invoke a command from the communications device (the repetitive PV command).
5. Observe the waveform across the DUT. Use the trigger delay to locate the negative edge of the RTS signal.
6. Compare the start of carrier waveform to the waveshape shown in Figure 44.

Carrier Stop/Decay

1. Connect one channel of the scope across the DUT.
2. Connect the second channel to the IRTS pin of the HART modem and use the positive edge as the trigger to the sweep.
3. Adjust the output of the unit under test to mid-scale output.
4. Invoke a command from the communications device (the repetitive PV command).
5. Observe the waveform across the DUT.
6. Use the trigger delay to locate the positive edge of the RTS signal.
7. Compare the end of carrier waveform to the waveshape shown in Figure 45.

13.2.5 Notes on Carrier Timing

1. The RTS signal generated at the modem is used to trigger the scope. The trigger can be applied to the external trigger input or to a second input channel on the oscilloscope. Typically, there is a DC offset between the modem and the analog current, therefore the probe connected to RTS must not have its ground connected to the modem's ground. The oscilloscope's trigger will need to be adjusted to compensate for the DC offset between the modem and the loop current. Use a positive trigger for end of carrier and a negative trigger for start of carrier.
2. For those devices without a RTS signal available, the test must be conducted by analysis. The analysis would show (via timing diagrams and circuit analysis) that the carrier will start and stop within the Physical Layer requirements.
3. When performing the Carrier Decay test, it is only necessary to verify that the carrier amplitude falls below the 'noise floor' within the specified time. Verification that carrier amplitude falls below the 2.2 mVRMS Output Noise During Silence specification is not necessary.

13.2.6 Example Test Data

The following are examples of a conforming HART device.

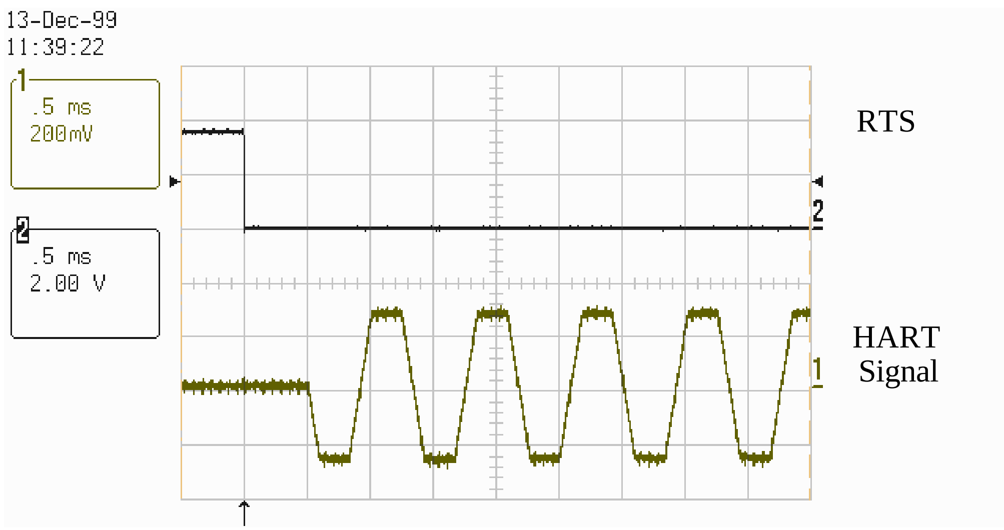


Figure 47. Sample Waveform Carrier Start

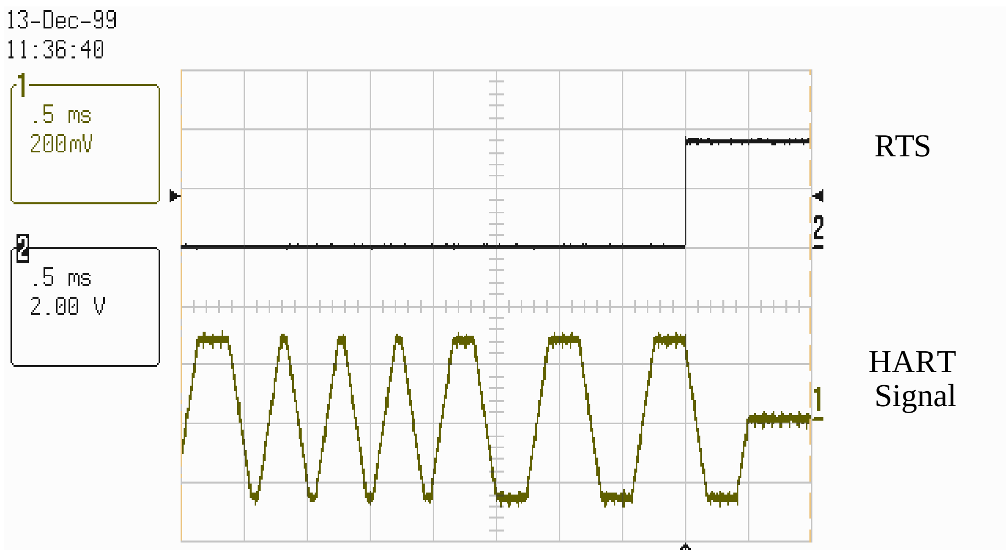


Figure 48. Sample Waveform Carrier Stop

13.3 Carrier Start/Stop Transient

When a HART device begins or ends transmission, a transient spike should not be introduced into the network (see Figure 49 below). Large transients could interfere with the reception of HART signals by other devices or, more importantly, affect analog signaling. This test insures that transients remain within a range that does not interfere with analog signaling.

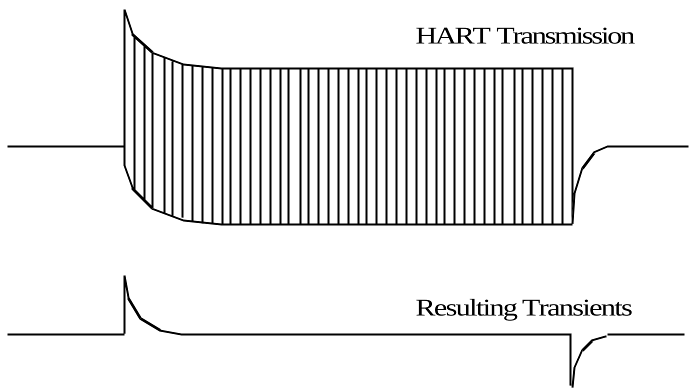


Figure 49. Carrier Start Transient

13.3.1 Requirements

The Physical Layer requires when passing a signaling waveform through the analog filter (see Section 10.8, Test Filters), carrier start/stop transients should decay quickly enough that filter output does not exceed 100 mV[3] above or below the DC average of the filter output.

These requirements do not apply to the application or removal of a network connection (i.e., temporary connection of a secondary master).

13.3.2 Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. Test load resistor (Table 1)
2. Oscilloscope
3. PC and Software
4. DC Power Source
5. Analog Test Filter (HCF_TOOL-32)

3. Revision 8.1 Physical Layer Specification specifies 10mV, not taking into account the 10X filter gain.

13.3.3 Test Setup

Refer to Figure 29 through Figure 39 in Section 12 for device-specific test setups.

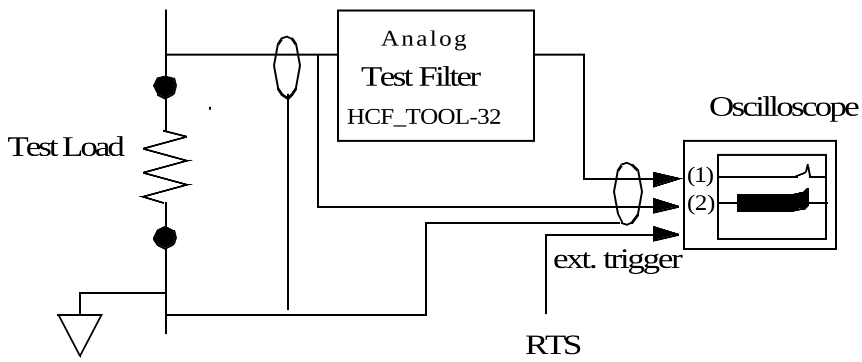


Figure 50. Carrier Transient Test Setup

13.3.4 Test Procedure

The start/stop transient characteristics are measured with an oscilloscope connected to the analog test filter or the test circuit, depending on the test set-up shown above. The test requires that measurement be performed during the start and the stop of a HART message.

Slave Device

Using the HART master (PC and software) to assert a request to the slave test device, monitor the beginning (or the end) of the reply and the output of the low-pass filter with an oscilloscope. The oscilloscope should be connected to the input and output of the Analog Test Filter and be triggered with the RTS line of the modem circuit.

Master Device

Use the HART master (PC and software) under test to assert a message across the test load. The oscilloscope should be connected to the input and the output of the analog test filter to monitor the beginning and the end of the request message. The scope should be triggered with the RTS line of the modem circuit.

13.3.5 Notes on Carrier Start/Stop Transient

1. The RTS signal generated by the modem is used to trigger the scope. The trigger can be applied to the external trigger input or to a third input channel on the oscilloscope. Typically there is a DC offset between the modem and the analog current, therefore the probe connected to RTS must not have its ground connected to the modem's ground. The oscilloscope's trigger will need to be adjusted to compensate for the DC offset between the modem and the loop current. Use a positive trigger for end of carrier and a negative trigger for start of carrier.

2. Typically, a long stop transient is characteristic of excessive capacitance on the Output Transmit Analog circuitry.

13.3.6 Example Test Data

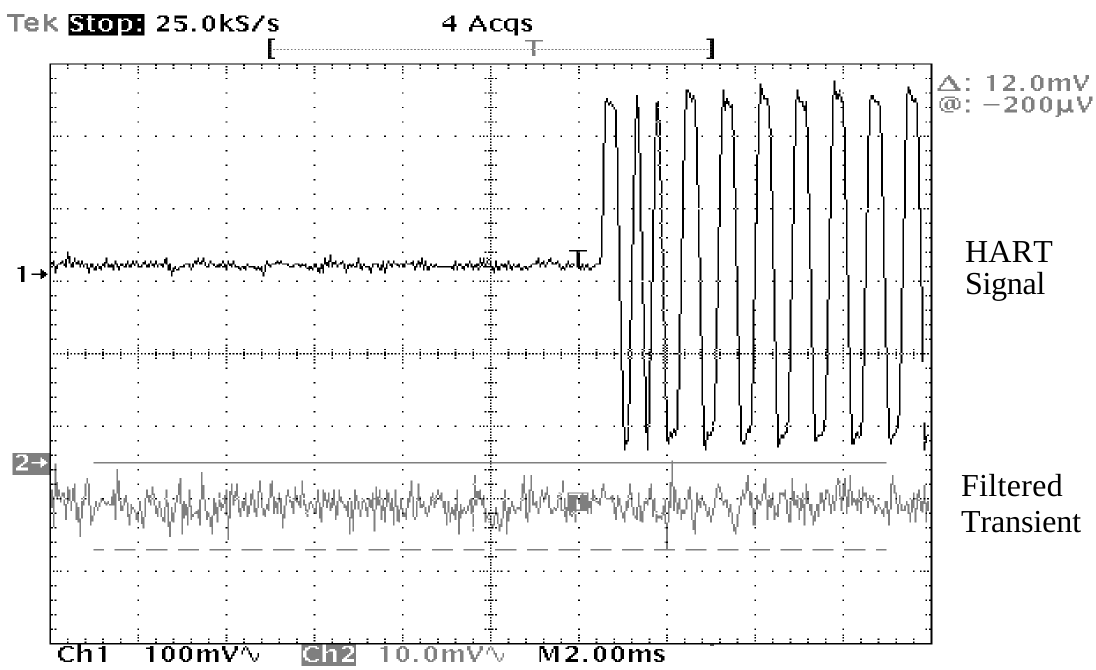


Figure 51. Sample Waveform Carrier Start Transient

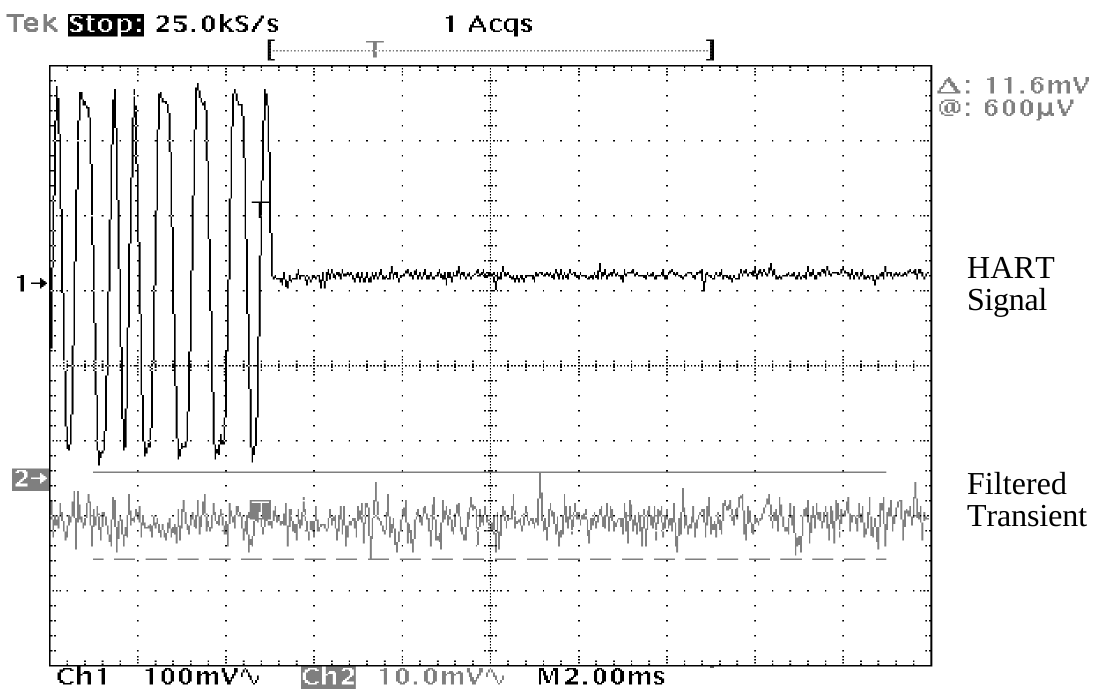


Figure 52. Sample Waveform Carrier Stop Transient

13.4 Output Noise During Silence

When a HART device is not transmitting (Silence), noise should not be coupled onto the network in the HART Extended Frequency Band. Excessive noise may interfere with reception of HART signals by the device itself or other devices residing on the network. Noise from one device may seem minimal but effects are additive with HART devices connected in a multidropped configuration.

13.4.1 Requirements

During silence, the element output voltage, averaged over 1 second or more, must contain not more than 2.2mV RMS of combined broadband and correlated noise in the Extended Frequency Band. Devices capable of Analog Signaling must meet this requirement with the device adjusted to produce a constant analog output current. Allowable noise levels above and below the Extended Frequency Band are shown in Figure 53. In the frequency spectrum above the Extended Frequency Band, the curve depicts a level of 138 mV RMS which is not a requirement but simplifies the test[4].

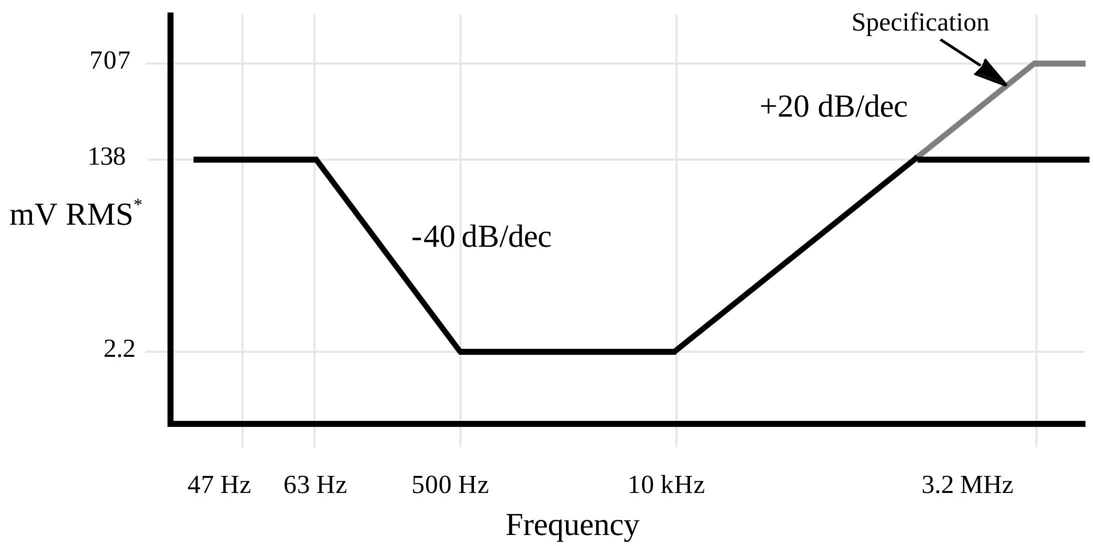


Figure 53. Allowable Output Noise

4. The reduction in allowable noise levels in the test procedure (not the specification) may infrequently result in conformant device failure for the Output Noise During Silence test. Devices that fail this test will be evaluated to determine if the noise level is excessive.

13.4.2 Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. Test Load Resistor (Table 1)
2. Digital Oscilloscope capable of RMS measurements
3. Digital Filter, HCF_TOOL-31
4. DC Power Source (Battery power recommended for loop powered devices)

   Note: Three 9 volt batteries in series provide a low noise 27 VDC power source.

5. RMS Digital Voltmeter

13.4.3 Test Setup

The setups illustrated in Figure 54 and Figure 55 are used for testing output noise. Refer to Figures 29 through 39 in Section 12 for device-specific test setups.

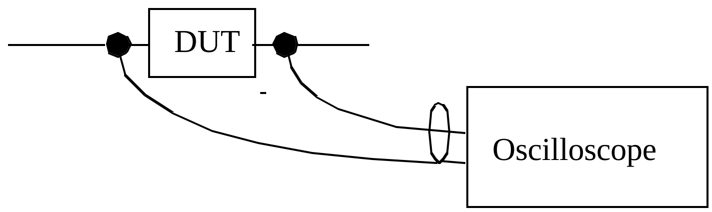


Figure 54. Output Noise During Silence Test Setup without Filter

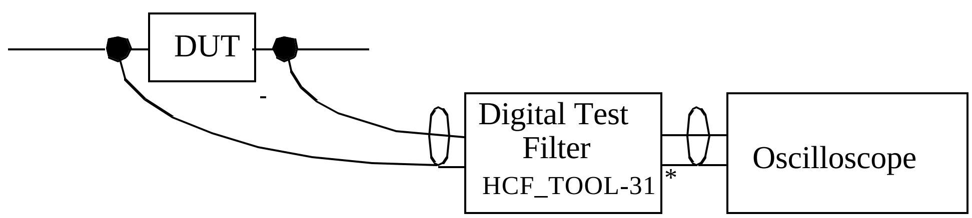


Figure 55. Output Noise During Silence Test Setup with Filter

13.4.4 Test Procedure

The noise test requires two measurements across the DUT. First, a measurement to detect noise outside the Extended Frequency Band **without** the filter connected across the DUT. Second, a measurement to detect noise within the Extended Frequency Band **with** the bandpass filter applied. The test requires the noise measurement to be performed during the non-communicating state (silence) of the HART device.

When testing a loop powered device, batteries are recommended to power the device. This insures the loop power supply noise is not also measured. Self-powered devices must be powered as they will be in normal use.

1. <u>Testing Without a Filter</u> (Noise outside the Extended Frequency Band)

   The unfiltered output noise characteristics are measured and recorded with an oscilloscope connected across the DUT. The DUT must generate less than 138 mV RMS of noise.

   > *Note*: For ease of testing the test criteria (138 mV RMS) is more restrictive than specified by treating the noise above the Extended Frequency band the same as the noise below. For devices that fail this test, further evaluation will be required to determine if the failure was due to noise above the Extended Frequency Band and if it is with the specified limit as shown in Figure 53.

   If the measured noise level is less than 2.2 mV RMS without use of a filter as described above, the DUT can be considered conformant and no further noise testing is required.

2. <u>Testing With a Filter</u> (Noise within the Extended Frequency Band)

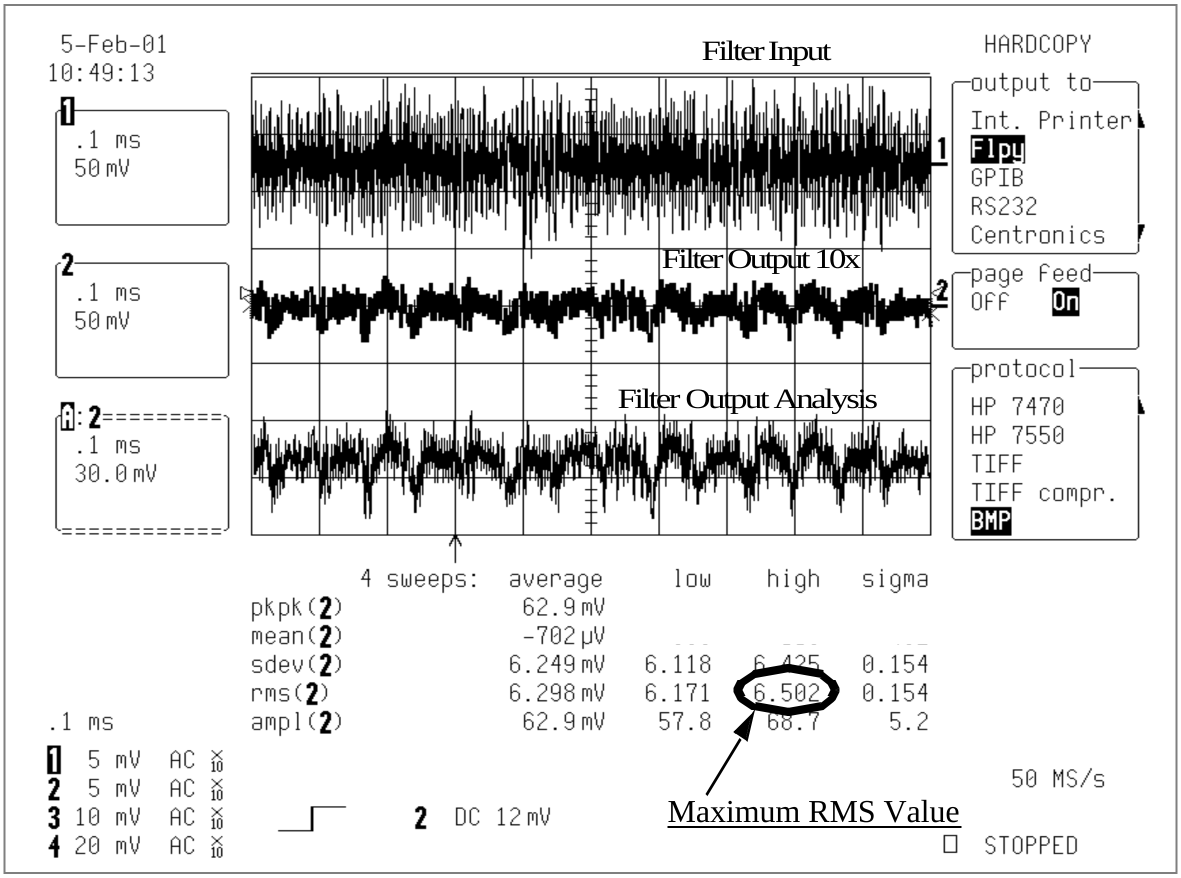
   Testing with a filter, the filtered output noise characteristics are measured and recorded with an oscilloscope connected to the output of the filter. The DUT must generate less than 2.2 mV RMS of noise. The output of the test filter must be less than 22 mVRMS since the filter has a gain of 10. The HCF Digital test filter is designed to measure only the noise in the extended frequency band spectrum (500 Hz- 10 kHz).

13.4.5 Notes on Output Noise During Silence

1. The specification requires the noise to be measured for 1 second. In almost all cases, the noise measurement will be the same for 1 second as it would be for 1 minute. The preferred method for measuring the noise would be to use an oscilloscope with an ‘envelope’ mode to capture the worst-case peaks in noise amplitude over a one second duration.
2. RMS noise is best measured with using a digital oscilloscope capable of measuring the signal in true RMS. A RMS digital voltmeter can be used as well providing it has adequate bandwidth.

13.4.6 Example Test Data

The following is an example of output noise with the digital test filter:



Note: Any form of signal filtering with an oscilloscope or external circuit is not allowed.

Above scope picture captures the filter's input and output with the top 2 traces. The lower trace performs a math function to the filter's output to determine the maximum true RMS value of the noise in the Extended Frequency Band. In this example the noise is 6.502 mV RMS, within the 22 mV RMS criteria.

Figure 56. Sample Waveform Filtered Output Noise

13.5 Analog Rate of Change

This test applies to current controlling devices (transmitters or current output devices) only. Voltage mode devices are not addressed by this procedure.

When a device regulates current proportional to the process it is measuring, the maximum rate of change of analog current should not interfere with HART communications. Step changes in current will disrupt HART signaling. The analog signaling test evaluates the device's resultant analog current during process changes and its ability to communicate HART under worst-case conditions.

13.5.1 Requirements

1. The analog output signal generated by an analog signaling device (i.e., transmitter or current output device) must be limited in its characteristics so that worst-case current signaling waveforms, when applied to the specified test load and passed through the Digital Test Filter, do not produce any instantaneous peak voltages above 150 mV[5] at the filter output.
2. The device must be capable of successful communication (bit error rate < 1 in 10,000) during worst-case analog signaling with the received HART signal attenuated to 145mVpp amplitude.
3. The test must be performed at worst-case sensor turndown with damping set to its minimum, if applicable.

13.5.2 Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. Test Load Resistor
2. Oscilloscope
3. Simulated Sensor or Modified Test Device Software (see Section 13.5.3, Analog Rate of Change Test Setup)
4. PC and Software
5. PhL Test Interface
6. Digital Filter (HCF_TOOL-31)
7. DC Power Source

5. Revision 8.1 Physical Layer Specification specifies 15mV, not taking into account the 10X filter gain

13.5.3 Analog Rate of Change Test Setup

Two tests are performed to test the Analog Rate of Change of an analog signaling device. Analog Signaling evaluates the device's analog current during process changes. Communication/Signalling tests the device's ability to communicate HART under worst-case conditions. The setups for each test are described below. Refer to Figure 34 for device-specific test setup.

<u>Analog Signaling Test Setup</u>

The test setup shown in Figure 57 is used for measuring the level of analog signaling created by a transmitter varying its analog signal at its extreme rates.

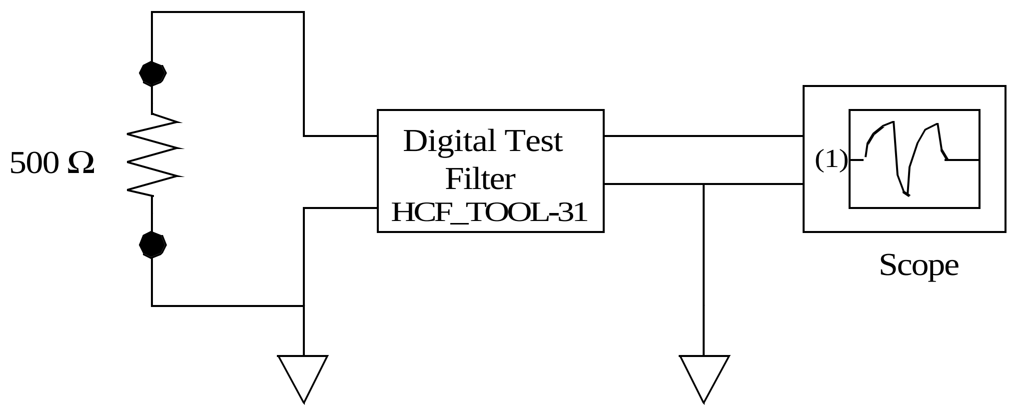


Figure 57. Analog Signaling Test Setup

<u>Communication/Signaling Test Setup</u>

The test setup shown in Figure 58 is used when testing the effects of communications during analog signaling. This test must be performed at worst-case conditions.

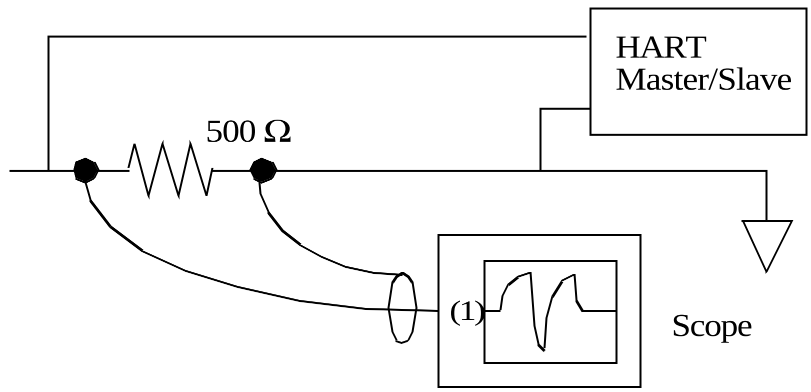


Figure 58. Communication/Signaling Test Setup

13.5.4 Test Procedures

Analog Signaling Test Procedure

The intent of the test is to change the output current full scale with the use of a sensor simulator or modified device test software. The resulting change in loop current is converted to a voltage across the current sense resistor, passed through the specified bandpass filter, and its magnitude measured with an oscilloscope. The output of the filter observed on the oscilloscope should not exhibit a peak voltage (instantaneous voltage at any point relative to 0 V) greater than 150 mV.

Set and record the worst-case sensor range down and damping (If applicable, set damping to its minimum). The device should cycle from zero to full scale such that its output does reach zero and full scale as shown in Figure 59:

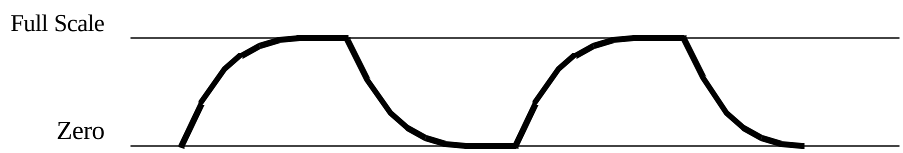


Figure 59. Example Full Scale Analog Signaling

Communication/Signaling Test Procedure

While the test device is cycling its output full scale under worst-case signaling conditions from the PC/modem signaling with 145 mVpp, use the HART master/slave simulator to assert 100 requests for data and monitor the number of successful replies. No errors are allowed. Record signal amplitudes across the test load and the number of communication errors.

13.5.5 Notes Regarding Analog Rate of Change

1. This test requires the DUT to modulate analog current full scale in both directions at rates representative of the worst-case application. The device manufacturer should provide a process simulator and/or test software to simulate this worst-case current change. The changing current can be generated using a simulated sensor (as shown in Appendix A), when testing a Transmitter device, or modified device software, when testing a current output device.

2. To trouble shoot a device that fails this test, the test should be conducted without analog signaling to determine if the problem exists within the application layer rather than the physical layer.

13.5.6 Example Test Data

The following is an example of the effects of analog signaling as captured at the output of the Digital Test filter.

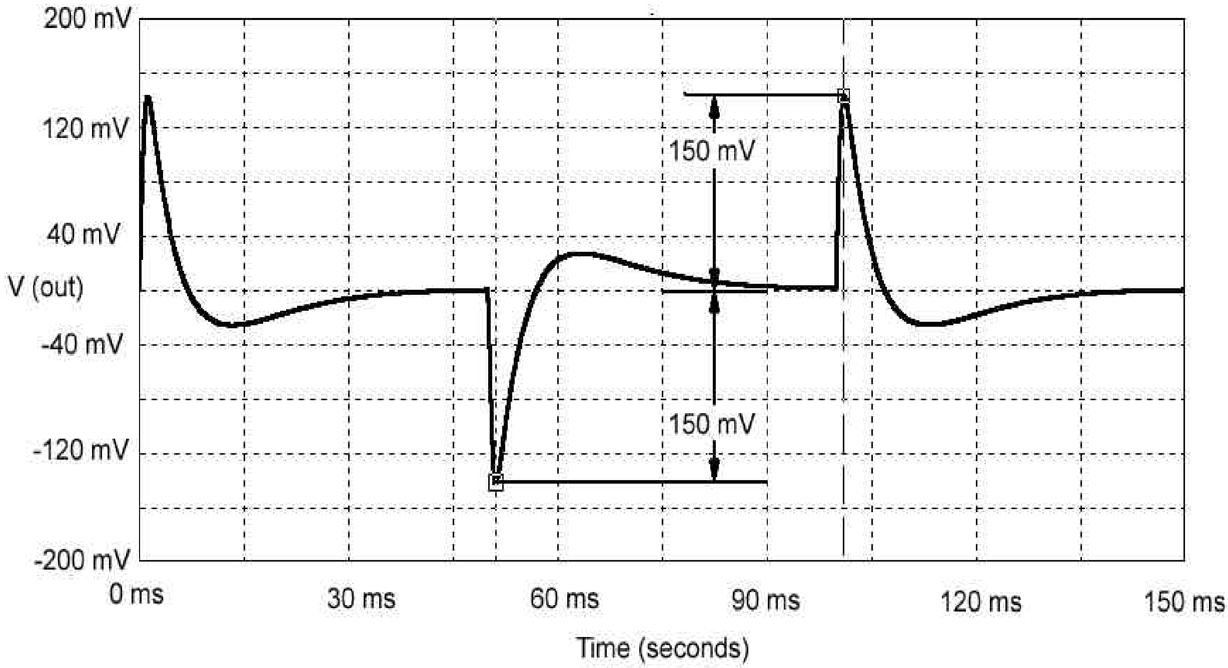


Figure 60. Analog Signaling Waveform

13.6 Receive Impedance Measurement

Impedance measurements are required for all devices. Impedance directly impacts the distances over which signaling is possible and the number of multidropped devices that can reside on a network. The intent of the impedance test is to verify that device impedance requirements are satisfied.

It is possible for a device to have good terminal-terminal parameters but poor terminal-ground parameters. This would be particularly troublesome for a Secondary device which is not connected to the network when it is analyzed. Excess resistive or capacitive leakage to ground can have the undesirable effect of increased noise coupling and/or stray currents.

Calculation of input impedance requires characterization of the following parameters:

1. *Equivalent Device Capacitance, C_X*
   Used to determine the maximum network cable length over which HART communications is theoretically possible. A device with high input capacitance may greatly reduce the distance of successful HART signalling.
2. *Equivalent Device Resistance, R_X*
   Used to determine the maximum network cable length over which HART communications is theoretically possible. A device with low input resistance may greatly reduce the distance of successful HART signalling.
3. *Capacitance Terminal-to-Ground, C_{tg}*
4. *Resistance Terminal-to-Ground, R_{tg}*

13.6.1 Requirements

1. *High Impedance Devices*
   High impedance devices have no pass/fail criteria, only recommended minimum values as described in Table 9 below. The R_X and C_X values are worst-case terminal-to-terminal parameters to be determined from impedance magnitude measurements at several frequencies and with two different ground configurations. A worst-case configuration will have the lowest obtainable impedance value (i.e., the smallest R and the largest C values). In general, worst-case capacitance is a result of terminal-to-ground capacitance.

Table 9. High Impedance Device Electrical Characteristics

Parameter	Condition	Limits
Device Capacitance, C_X	Receive	5000 pF (recommended max.)
Device Resistance, R_X	Receive	100 kΩ (recommended min.)

2. *Secondary Devices*
   Secondary devices require a minimum impedance as shown in Table 10 below. These requirements also apply to polarized units with reversed connections, whether or not power is applied.

Table 10. Secondary Device Electrical Characteristics

Parameter	Condition	Limits
Impedance Magnitude, Z_m (terminal-to-terminal)	Receive, Normal Frequency Band	5 kΩ min.
Capacitance, C_{tg}, (terminal-to-ground)	Send or Receive	250 pF max.
Resistance, R_{tg} (terminal-to-ground)	Send or Receive	100 kΩ min.

3. *Low Impedance Devices*
   Low-Impedance devices require an impedance within the range specified in Table 11 below:

Table 11. Low Impedance Device Electrical Characteristics

Parameter	Condition	Limits
Impedance Magnitude, Z_m (terminal-to-terminal),	Receive Normal Frequency Band	230 Ω to 600 Ω (Note 1)
Impedance Magnitude Variation, ΔZ_m	Receive Extended Frequency Band	+/- 3 dB

Note 1: No test load should be connected in parallel with the DUT when measuring impedance. Measurements include the device's current sense impedance (e.g., a 250 Ω sense resistor on a Current Input).

13.6.2 Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. Test Resistors, 250 Ω and 5000 Ω.
2. Kepco Bipolar Power Supply or equivalent (See Appendix B)
3. Oscilloscope
4. RMS Voltmeter (Bandwidth ≥ test frequency)
5. Function Generator
6. Digital Volt Meter (DVM)
7. Capacitance Bridge or Meter

13.6.3 Test Setup

An approximation of the device input impedance can be measured using either of the simple test circuits diagrammed in Figure 61 and Figure 62. Test circuits for devices requiring a DC bias (e.g., loop powered devices) are constructed with a frequency source to generate a sinusoidal signal that modulates the DC power signal. To test the circuit set up, replace the DUT with a known parallel resistor and capacitor to simulate the impedance of a test device and perform the test to obtain a representative impedance curve.

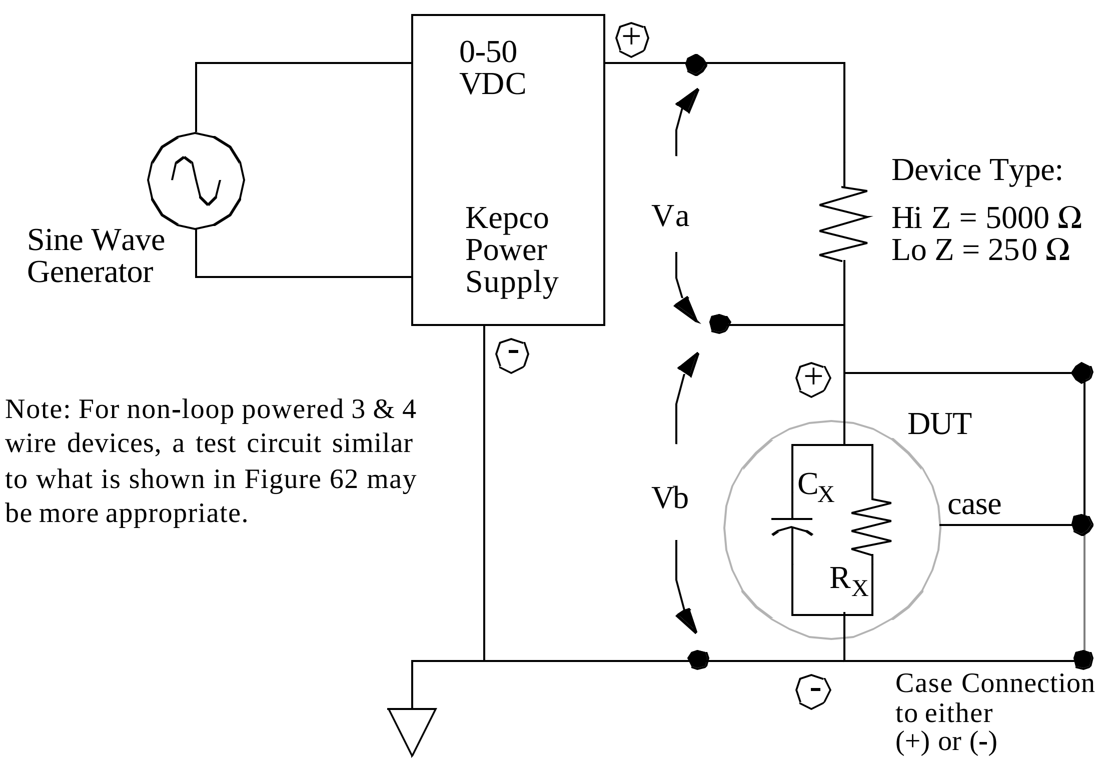


Figure 61. Impedance Test Circuit with DC Bias

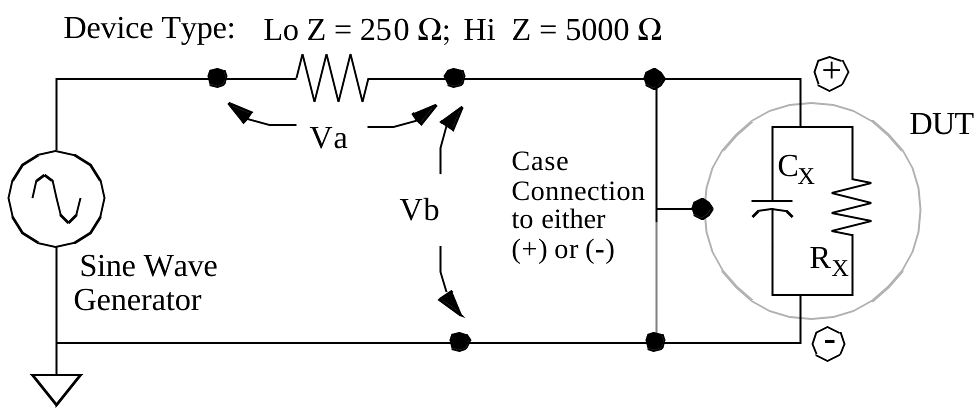


Figure 62. Impedance Test Circuit with No DC Bias

13.6.4 Receive Impedance Test Procedure

This test is intended to measure impedance magnitude within and well beyond the HART Normal Frequency Band while the DUT is silent (non-transmitting). Impedance characteristics may vary with loop current but need to be determined only at the multidrop current value. Measuring the magnitude of the impedance as a function of frequency determines whether device impedance characteristics meet or exceed required or recommended values.

Calculate Impedance Magnitude

1. For Transmitter & Non-DC Isolated devices, the DC loop voltage provided by the Kepco power supply must be set so the DUT is within its normal DC operating voltage or current range. In the case of high impedance devices where the 5000 Ω test resistor is used, the DC voltage required to power the DUT may be quite high and the Kepco supply must be adjusted accordingly.

2. With the appropriate test circuit as shown in 13.6.3, use an oscilloscope to measure the differential voltage magnitudes of V_a and V_b as a function of frequency.

3. Connect the (+) lead of the DUT to its metal case. The connection of the case or chassis of the DUT to the (+) or (-) network connection is only necessary for devices with circuitry that is DC isolated from ground.

   Devices that are not DC isolated from ground (e.g., most devices that supply current to the network) need only have the impedance measured in the normal operating ground configuration. The nature of the ground reference must be stated in the test results, as in this example: “The (+) terminal of this Current Input device is tied directly to the DCS system 24V power supply through a fuse. The (-) terminal connects through a 250 Ω sense resistor to Analog Power Supply Common of the DCS system.”

4. Adjust the sine wave generator for 1Vpp as measured across the DUT or the series loop resistance.

5. Record test data from 200Hz to 10kHz for high impedance devices, from 500Hz to 50kHz for Low-Impedance devices, and 950Hz to 2.5kHz for Secondary devices as listed on the test data sheets.

6. Repeat steps 2 through 5 with the (-) lead of the DUT connected to its metal case (see step 3). A case connection is not necessary for secondary devices, however the test must be performed four times with device polarity interchanged while powered and unpowered.

7. Calculate the impedance magnitude, Z_m, at each test frequency using the following equation. Record the values on the chart provided on the results sheet.

$$Z_m = \frac{R}{V_a} \times V_b$$

V_a is measured differentially with an oscilloscope or RMS voltmeter. Due to possible phase differences in the test circuit, V_a is not necessarily equal to the difference in magnitude between the voltage source and V_b.

8. Using the worst-case data (lowest impedance value, Z_m, of the two tests at each frequency) as the DUT's impedance estimate for each frequency, plot the data on the provided data sheet graph.

9. Estimate the R_X and C_X values by plotting the impedance magnitudes at the test frequencies on the graph in Figure 63 (for high impedance and secondary devices) or Figure 64 (for low impedance devices). These graphs include curves for various R_X and C_X values. The curves assume an RC equivalent circuit.

   The best R and C values will be represented by a curve that will fit just under the data points. For example, a high impedance device that meets the recommended values will have test data above the 100k/5000 pF curve in Figure 63. A device that does not meet the recommended values will have data below the curve and will need to claim RX and CX values for which the curves would fall below the actual data. Any device for which the impedance magnitude decreases with decreasing frequency can be assumed to have an R_X value equivalent to the highest impedance magnitude observed in the Normal Frequency Band of 950 Hz to 2.5kHz. The C_X value may be established from the impedance magnitudes at and above the Normal Frequency Band.

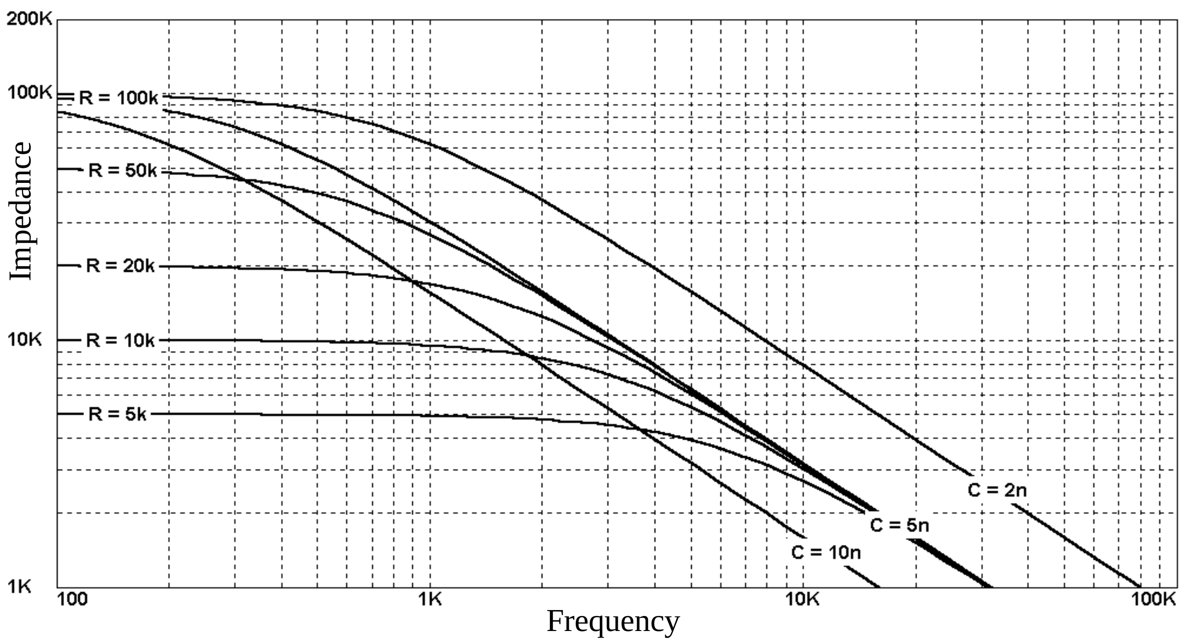


Figure 63. High Impedance Device Characteristics

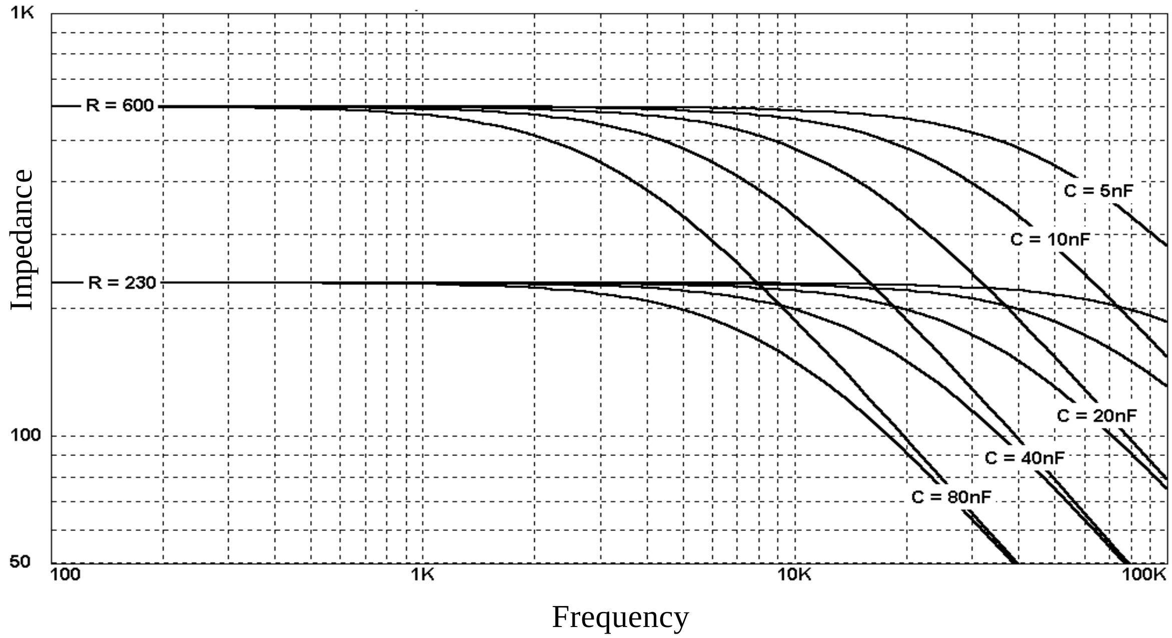


Figure 64. Low Impedance Device Characteristics

<u>R_{tg} and C_{tg} measurement</u>

Devices that are ground-referenced (e.g., most devices that provide power for a network), will have a very low R_{tg} value for at least one terminal. The measured values should still be recorded.

1. With the test device not powered, measure with a DVM and/or Bridge the Resistance and Capacitance characteristics from each terminal to its chassis ground and record these values in the data sheet.

   Most field devices have electronic circuitry that is DC isolated from ground, but also have a case or chassis that is normally grounded. The terminal-to-ground parameters (R_{tg} and C_{tg}) are measurements taken between the loop connections to the device and the case or chassis that is normally grounded. If a device such as a handheld Secondary device has a case that is non-conductive and the chassis is not normally ground-referenced, the device can be assumed to meet the requirements and "NA" can be written in for the R_{tg} and C_{tg} parameters.

13.6.5 Notes Regarding Receive Impedance Measurement

1. For the DUT's case to be connected to the (+) and (-) terminals, the case must be electrically floating with respect to the test circuit and equipment.

2. A 5000 Ω test resistor is used for testing high impedance and secondary devices to increase the sensitivity and accuracy of the measurement.

3. While impedance is tested over a larger frequency range, the only values used for comparison to the impedance magnitude requirements are those in the Normal Frequency Band of 950 Hz - 2500 Hz. Values outside the Normal Frequency Band that fall outside the requirements are not considered in the impedance criteria. These values are however necessary to establish an accurate estimate of the device R_X and C_X parameters used in the Network Length Determination.

4. If the signal across the series resistance does not remain sinusoidal and undistorted, it may indicate complex internal impedance or clamping of the input signal. Significant distortion may invalidate the test method and should be understood (prevented if possible). The use of a voltmeter for these measurements is also invalid if there is significant distortion.

5. 3-wire and 4-wire devices:

   The test set-up for 3-wire and 4-wire devices may vary from what is shown in Figure 61 and Figure 62.

   For a 3-wire device that sinks current, Figure 61 would be used with DUT power applied in a similar manner as shown in Figure 35.

   For a 4-wire device that sinks current, Figure 61 would be used with DUT power applied in a similar manner as shown in Figure 36. The DUT power supply needs to be isolated from the Kepco power supply.

   For a 4-wire device that sources current, the Kepco power supply would be in series with the DUT internal supply in a similar manner as shown in Figure 35. The Kepco supply voltage should be kept to a minimum so that the DUT does not have excessive voltage across its terminals.

13.6.6 Example Test Data

The following is an example of a High Impedance device with R_X = 100kΩ and C_X = 3000pF.

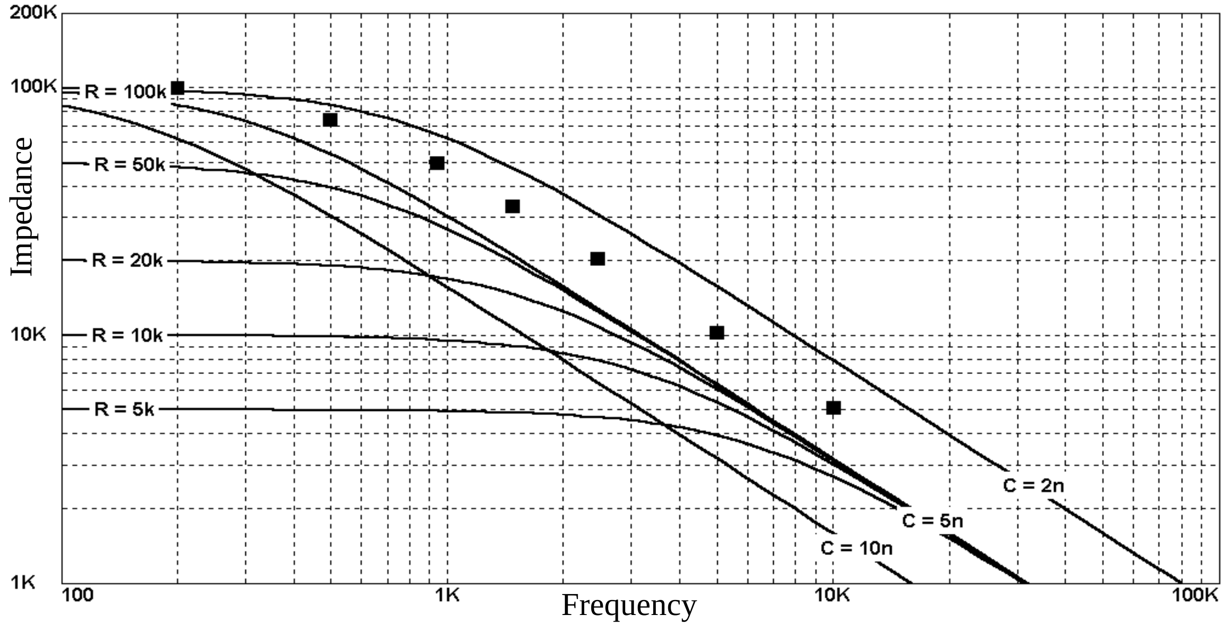


Figure 65. Sample High Impedance Test Data

The following is an example of a Low Impedance device with R_X =400 Ω and C_X = 30000pF.

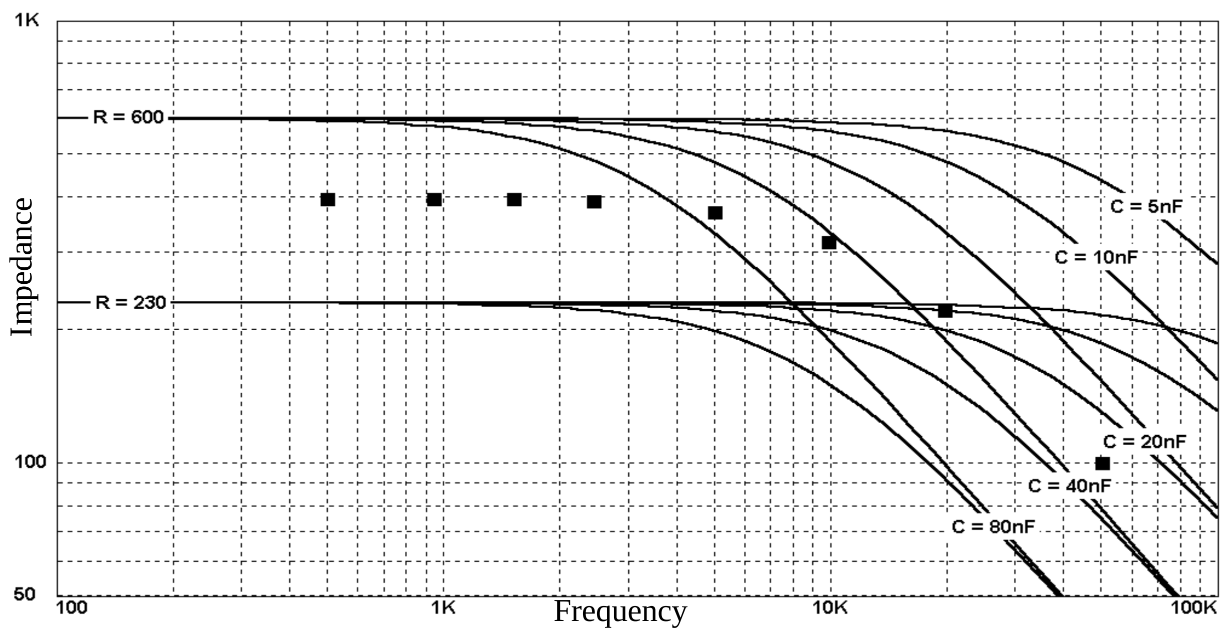


Figure 66. Sample Low Impedance Test Data

13.7 Send Impedance Measurement

This test is only for low impedance & secondary devices.

13.7.1 Requirements

Table 12. Device Electrical Characteristics

Device Type	Parameter	Condition	Limits
Low Impedance Devices	Impedance Magnitude, terminal-to-terminal	Send only	(Note 1)
Secondary Devices	Real part of impedance, (terminal-to-terminal)	Send	(Note 1)
	Imaginary part of impedance, (terminal-to-terminal)	Send	(Note 1) (Note 2)
	Capacitance, C_{tg} (terminal-to-ground)	Send or Receive	250 pF max.
	Resistance, R_{tg} (terminal-to-ground)	Send or Receive	100 kΩ min.

Note 1: Send Impedance may not exceed the receive-only impedance.

Note 2: Meeting the waveform characteristics satisfies the transmit reactance requirements.

Since substantially different measurement methods are required for send and receive impedances, and since these methods are inexact, the requirement that the send impedance be less than or equal to receive impedance can be considered to be met if the send impedance is less than or equal to 120% of the receive impedance.

13.7.2 Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. Oscilloscope
2. Resistive Decade Box
3. Test Load Resistor(s)
4. RMS Digital Volt Meter (DVM)

13.7.3 Send Impedance Test Setup

The send impedance for a secondary device can be measured with the use of a simple test circuit as shown below:

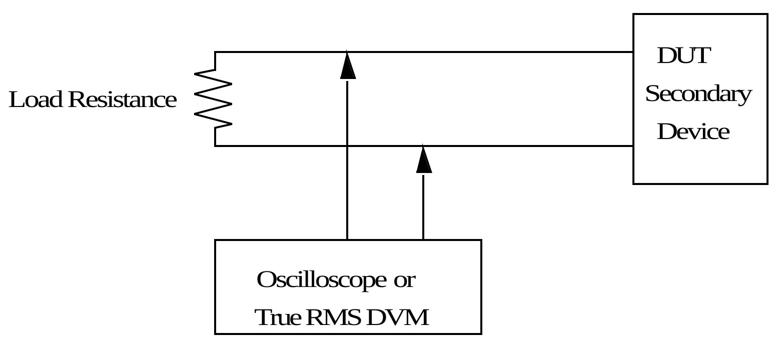


Figure 67. Secondary Send Impedance Test Circuit

The send impedance for an Actuator Device can be measured with the use of a simple test circuit as shown below:

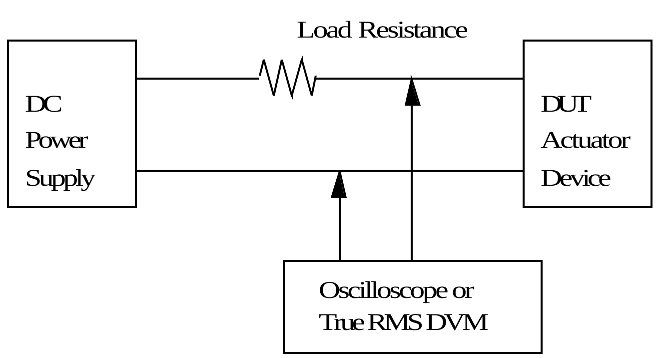


Figure 68. Actuator Send Impedance Test Circuit

The send impedance for a Current Input Device can be measured with the use of the simple test circuits as shown below:

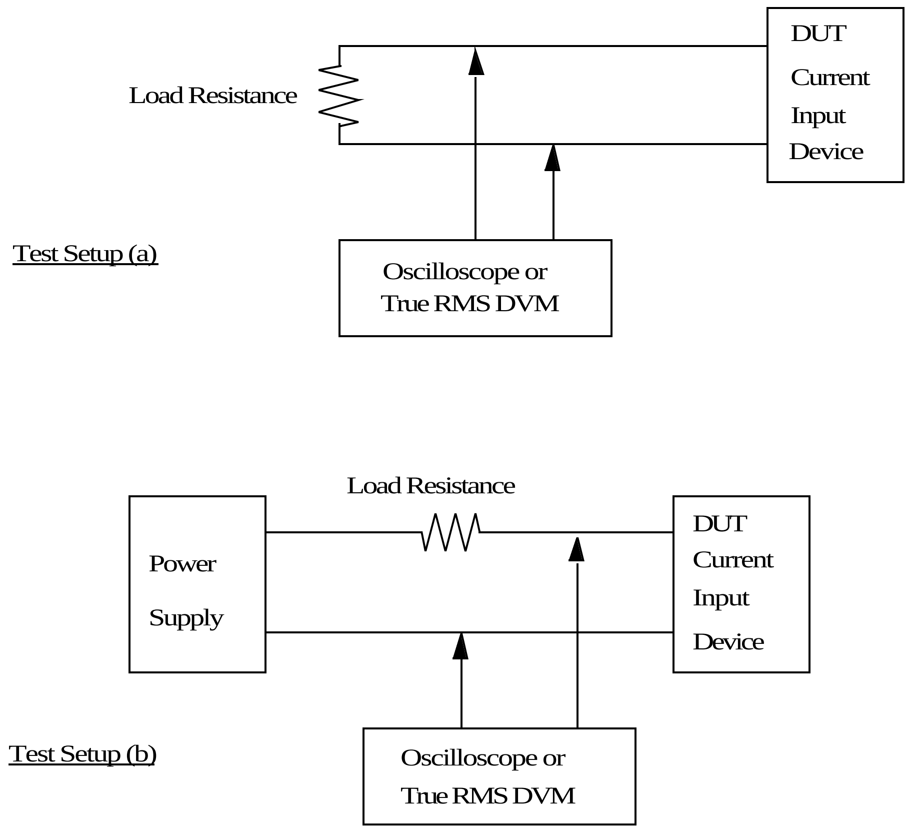


Figure 69. Current Input Send Impedance Test Circuit

13.7.4 Send Impedance Test Procedures

<u>Secondary Device</u>

1. Set up with 500 Ω load resistor as shown in Figure 67. Set the DUT to continuously transmit each frequency (1200 and 2200Hz). Measure the True RMS AC voltages (V1) at the terminals of the DUT[6].

2. Change the load resistor to 230 Ω. Set the DUT to continuously transmit each frequency (1200 and 2200Hz). Measure the True RMS AC voltages (V2) at the terminals of the DUT[6].

3. Calculate the send impedance for each send frequency (1200 and 2200Hz) from the signal RMS voltage loss as follows:

$$\text{Send Impedance} = Z_{out} = \frac{\Delta V}{\Delta I} = \frac{V1 - V2}{I2 - I1} = \frac{V1 - V2}{(V2 \div 230\ \Omega) - (V1 \div 500\Omega)}$$

<u>Actuator Device</u>

1. Set up with 5 kΩ resistor and a power supply. Adjust power supply voltage for 4mA DC loop current (about 32 VDC depending on DUT terminal voltage). Set the DUT to continuously transmit each signaling frequency (1200 and 2200Hz). Measure the True RMS AC voltages (V1) at the terminals of the DUT for each frequency[6].
2. Change the load resistor to 1 kΩ. Reduce the power supply voltage to yield the same DC current (4 mA DC) as above. Set the DUT to continuously transmit each signaling frequency (1200 and 2200 Hz). Measure True RMS AC voltages (V2) at the terminals of the DUT[6].
3. Calculate the send impedance for each frequency (1200 and 2200 Hz) from the signal RMS voltage loss as follows:

$$\text{Send Impedance} = Z_{out} = \frac{\Delta V}{\Delta I} = \frac{V1 - V2}{I2 - I1} = \frac{V1 - V2}{(V2 \div 1\ k\Omega) - (V1 \div 5\ k\Omega)}$$

<u>Current Input Device</u>

1. Setup (b) in Figure 69 is only necessary if the current input circuit needs to be DC biased to operate properly.
2. Set up with 10 kΩ resistor. Set the DUT to continuously transmit each frequency (1200 and 2200 Hz). Measure the true RMS AC voltages (V1) at the DUT terminals[6].
3. Change the load resistor to 1 kΩ. Set the DUT to continuously transmit each frequency (1200 and 2200 Hz). Measure the True RMS AC voltages (V2) at the terminals of the DUT[6].

6. As an alternative to setting the DUT to continuously transmit each signaling frequency, a storage scope may be used to capture actual messages and the waveforms can be digitized and analyzed to determine the true RMS Voltage of each frequency segment. The captured waveforms may also be used to verify an acceptable waveshape.

4. Calculate the send impedance for each frequency (1200 and 2200 Hz) from the signal RMS voltage loss as follows:

$$\text{Send Impedance} = \text{Zout} = \frac{\Delta V}{\Delta I} = \frac{V1 - V2}{I2 - I1} = \frac{V1 - V2}{(V2 \div 1\ \text{k}\Omega) - (V1 \div 10\ \text{k}\Omega)}$$

13.7.5 Example Test Data, Low Impedance Device

The following are examples calculations for send impedance of conforming HART devices.

Secondary Device Zout *(V2 = 133 mV, V1 = 166.4 mV)*:

$$\text{Zout} = \frac{V1 - V2}{(V2 \div 230\ \Omega) - (V1 \div 500\Omega)} = \frac{0.1664 - 0.133}{(0.133 \div 230) - (0.1664 \div 500)} = 136\ \Omega$$

Actuator Device Zout *(V2 = 203 mV, V1 = 256.4 mV)*:

$$\text{Zout} = \frac{V1 - V2}{(V2 \div 1\ \text{k}\Omega) - (V1 \div 5\ \text{k}\Omega)} = \frac{0.2564 - 0.203}{(0.203 \div 1000) - (0.2564 \div 5000)} = 352\ \Omega$$

Current Input Device Zout *(V2 = 240 mV, V1 = 281.6 mV)*:

$$\text{Zout} = \frac{V1 - V2}{(V2 \div 1\ \text{k}\Omega) - (V1 \div 10\ \text{k}\Omega)} = \frac{0.2816 - 0.240}{(0.240 \div 1000) - (0.2861 \div 10{,}000)} = 197\ \Omega$$

13.7.6 Notes Regarding Send Impedance Measurement

1. Across the terminals of a device, low impedance characteristics (resistive or capacitive) are not usually encountered within the Normal Frequency Band. The exception would be the effect of the current sense resistor.
2. Testing a device implementing a HART Modem chip:
   On the modem, connect the RTS pin to VSS and the TXD pin to VDD. The modem should be transmitting a constant 1200 Hz signal. Repeat the above steps with TXD connected to VSS for a constant 2200 Hz signal.
3. Testing a master connected to a personal computer:
   Use test software[7] to generate constant 1200 Hz and 2200 Hz signals rather than manually invoking the device to transmit.

7. Test Software available from HCF; HCF_TOOL-39, Physical Layer Conformance Test Software, XMTR.

13.8 Noise Sensitivity Tests

Noise Sensitivity testing insures that the HART receiver is capable of reliably receiving valid messages through adverse noisy conditions. The noise sensitivity tests deal with receiver parameters. It is important to maintain the test voltages and waveforms as nearly ideal as possible, and it is not necessary to maintain the network impedance at the specified test load value.

13.8.1 Requirements

The device receiver characteristics are common for all devices and given in Table 13 below:

Table 13. Common Receiver Requirements

Parameter	Conditions	Limits
Amplitude of HART command at which Carrier Detect must be asserted		120 mVpp
Amplitude of HART command at which Carrier Detect must not be asserted		80 mVpp
Receive Signal Range	High Impedance Devices Low Impedance Devices	120 - 1500 mVpp 120 - 800 mVpp
Error Rate	Signal level 200 mVpp, Added Gaussian Noise of constant density of 163 microvolt/root Hz over the Extended Frequency Band, Pseudo-random bit sequence	1 in 10,000 max
Out-of-Band Interference with no degradation in receiver performance	0 Hz -500 Hz 10 kHz - 1 MHz	See FSK Physical Layer Specification for interference limits.
In-Band common mode Interference with no degradation in receiver performance	Extended Frequency Band 500 Hz - 10 kHz	0.2 Vpp max
Below-Band common mode Interference with no degradation in receiver performance	47 Hz - 500 Hz	2 Vpp Max

13.8.2 Test Equipment

Refer to Section 10, Physical Layer Test Equipment, for more detailed descriptions of required test equipment.

1. PC (2 required for testing modems)
2. PhL Test Interface, HCF_TOOL-35
3. DC Power Supply
4. Signal Generator
5. 250 Ω Resistor, 5%, 1/8 watt or greater.
6. Oscilloscope
7. PC and Software

   Slave tests require master emulation software (HCF_TOOL-25, COMTEST) for the PC connected to the reference modem.

   Master and modem device tests require slave emulation software (HCF_TOOL-39, Xmtr-MultiVariable) for the PC connected to the reference modem. The DUT must act as a master by either running as designed or interfaced to a second PC running master emulation software (HCF_TOOL-25, COMTEST).

13.8.3 Test Setup

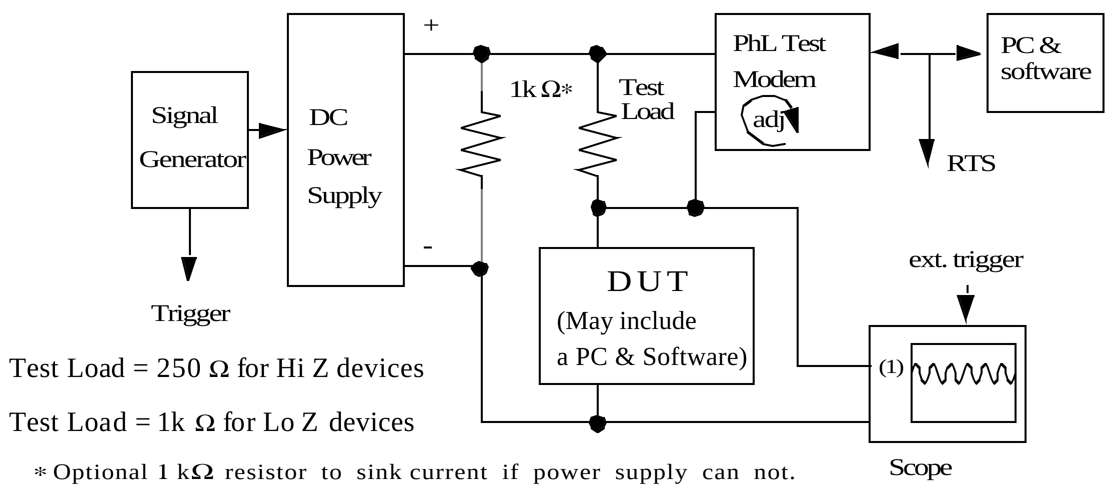


Figure 70. Noise Sensitivity Test Setup

Table 14. DC Power Supply Offset Voltage and PC Test Software

Device Type	DC Offset Voltage	Test Software
Transmitter or Non-DC Isolated	28 VDC (or as required)	HCF_TOOL-25
Secondary	0 VDC	HCF_TOOL-39
DC Isolated or Voltage Output	0 VDC	HCF_TOOL-25
Current Input or Voltage Input	6 VDC	HCF_TOOL-39
Actuator	15 VDC	HCF_TOOL-25
Current Output	12 VDC	HCF_TOOL-39

13.8.4 Test Procedure for all physical device types

1. Setup the test equipment as shown in Figure 70. Set all output levels to 0 before turning on the equipment, including the signal generator AC level, and the DC Power Supply DC offset.

2. Determine the appropriate DC operating condition for the DUT, and bring up the power supply voltage to the appropriate level to produce that condition. This level is DUT dependent and may be different than the voltage shown in the above table. For low impedance devices that accept analog signalling, the nominal center of the analog signalling range should be used (i.e. 12 mA).

3. Turn the signal generator ON but set the output amplitude at 0 (this is to ensure that the signal generator is exhibiting the same impedance as it will when producing the interference signal).

4. Set the level of the HART signal transmitted by the Reference Modem to 175 mVpp. To do this, activate the PC modem to begin communication with the DUT. Trigger the scope from the rising edge of the RTS signal from the PC to the Reference Modem, and observe the amplitude of the HART signal during this period. Adjust the gain control on the PhL Test Interface to obtain 175 mVpp signal amplitude at the terminals of the DUT. If the signal amplitude varies with frequency (e.g. the 2200 Hz signal is smaller than the 1200 Hz signal) the amplitude shall be set such that the lesser amplitude is 175 mVpp. At this condition, there should be no communication problems.

5. Set the noise signal frequency and voltage. To do this, stop the communications from the PC (or the DUT if it is a master). Trigger the scope from the Signal Generator noise source, to make it easier to observe the noise signal level. Set the frequency of the signal generator to the first test frequency i.e. 1700 Hz. Bring up the output

amplitude of the signal generator to where the oscilloscope indicates the desired amplitude of the interfering signal (i.e., 26 mVpp) as shown below in Table 15. If the DUT is low impedance, also check the amplitude across the test load resistor. The interfering signal should not produce more than 16mApp across this resistor.

Table 15. Noise Sensitivity Levels

Interference Amplitude Specification	Waveshape	Frequency	HART Signal
55 mVpp	Sinusoidal	1700 Hz	175 mVpp
220 mVpp	Sinusoidal	250 Hz	175 mVpp
880 mVpp*	Sinusoidal	125 Hz	175 mVpp
3.52 Vpp*	Sinusoidal	63 Hz	175 mVpp
16 Vpp*	Sinusoidal	29 Hz	175 mVpp

* For low impedance devices, this amplitude shall not be set high enough that the 4-20 mA operating range is exceeded

6. Resume communications, and verify an acceptable bit error rate. An acceptable error rate is adequately proven by 100 consecutive request-response exchanges without errors. Error detection may be accomplished by the test software in the PC or in the DUT.
7. Repeat 5 and 6 with the frequency and amplitude set to 250 Hz and 220 mVpp.
8. Repeat 5 and 6 with the frequency and amplitude set to 125 Hz and 880 mVpp.
9. Repeat 5 and 6 with the frequency and amplitude set to 63 Hz and 3.52 Vpp.
10. Repeat 5 and 6 with the frequency and amplitude set to 29 Hz and 16 Vpp.
11. If the DUT is a Voltage Output Device, put the DUT into a worst-case active analog signaling state by whatever means is appropriate. Worst-case is defined as full scale output variation at the maximum rate of change the equipment can produce under any foreseeable operating condition. Repeat steps in paragraph 5 above. (Note - the method for putting the device into worst-case will vary greatly depending on the type of equipment being tested and is beyond the scope of this procedure to define.)

13.8.5 Notes Regarding Noise Sensitivity

1. Since the Physical Layer Specification does not dictate the grounding schemes to be employed by various types of devices, (other than the Secondary which must be ungrounded) it is impractical to specify the appropriate ground connections to be used in the test setups. It is therefore up to the test engineer to determine the grounding practice to be used for the specified tests. An improperly grounded setup will generally cause problems rather than masking them.

2. This document does not require a test for common-mode noise immunity, because it may be beyond the scope of a simple test that may be run with ordinary test equipment. However, since common-mode noise appears to the typical field device DUT as a common-mode voltage difference between the network connections and the case, a simple test that may uncover common-mode susceptibilities may be performed by connecting the case of the instrument to a signal generator and modulating the case of the instrument relative to the network ground reference, with the specified signal, and conducting bit error rate tests as in the previous section.

3. This document does not require noise immunity testing above the HART extended frequency band, but such testing is highly recommended. The 20dB/decade high frequency rejection required by the Physical Layer Specification should make all HART devices immune to such noise levels as 550 mV @100 kHz and 5.5V @ 1 MHz.

13.9 Carrier Detect Tests

The purpose of testing carrier detect is to insure that a HART receiver will not demodulate random noise or low level coupled cross-talk messages. Conversely, the receiver has to be sensitive enough to hear low level signals that are attenuated over long cable lengths. In cases where the HART signal is unequal in amplitude between the 1200 Hz and 2200 Hz portions of the signal, the lesser of the two amplitudes is the critical one.

Testing the carrier detect start and stop timing ensures that receiver hardware introduces no delays in message handling to interfere with bus arbitration or unnecessarily reduce network throughput.

13.9.1 Requirements

1. The HART receiver must be designed to ignore signals less than 80 mVpp and reliably receive messages greater than 120 mVpp.

Table 16. Carrier Detect Specifications

Parameter	Limits
Amplitude at which Carrier Detect must be asserted	120 mVpp
Amplitude at which Carrier Detect must not be asserted	80 mVpp

2. The HART interface must detect assertion and disassertion of the carrier within the following limits:

Table 17. Carrier Detect Start/Stop Specifications

Parameter	Limits
Time from Carrier ON to Carrier Detect Assertion	6 bit times maximum
Time from Carrier OFF to Carrier Detect Disassertion	6 bit times maximum

3. Carrier Detect functions are most commonly implemented in one of two ways:

   - A circuit that detects the amplitude of the received signal which defines a logic state for all signals above 120 mVpp and its complement logic state all signals below 80 mVpp. The carrier detect output may be connected directly to the microprocessor (to an interrupt or port pin) or used to qualify the ORXD data going to the UART.

- The use of DC hysteresis with the receive filter. In that manner, all data that reaches IRXA of the modem has been pre-qualified with a predetermined signal level.

13.9.2 Test Equipment

The test equipment is identical to the equipment used for Noise Sensitivity Tests. If the Carrier Detect tests are set up separately, the setup may be simplified by omitting the signal generator from the Noise Sensitivity setups, and the Power Supply need not have modulation capability.

13.9.3 Test Setup

The test setups are identical to the equipment and setups used for Noise Sensitivity Tests (see Section 13.9.2, Test Equipment).

13.9.4 Carrier Detect Test Procedure

<u>Carrier Detect Level</u>

1. Bring up the power supply to the point where the DC operating condition of the DUT is established.
2. Start the communications software in the PC/Modem to repeatedly attempt communications with the DUT. The software emulates a Primary or Secondary Master for slave test devices and emulates a slave for master test devices.
3. Adjust the PhL Test Interface so that the amplitude of HART messages to the DUT (as measured at the DUT) is 120 mVpp. If the HART signal is distorted to the extent that the 1200 Hz and 2200 Hz signals are different in amplitude, the lesser amplitude should be set to 120 mVpp. Observe or record the HART signaling for several seconds. There should be no errors in the communication. The slave should respond to all the messages from the master.
4. Reduce the amplitude of the HART messages to 80 mVpp. If the HART signal is distorted such that the 1200 Hz and 2200 Hz signals are different in amplitude, the greater amplitude shall be set to 80 mVpp. Observe or record the HART signaling for several seconds. At this point, the master should not be receiving any valid responses from the slave. The best way to determine this will vary depending on the devices involved. If the DUT is a slave, there should NOT be any responses from it. If the DUT is a master, the slave emulator will be responding, but the master DUT should not hear the responses and should be issuing retries and/or reporting the loss of connection to the slave.

5. Increase the amplitude of the HART signal to the DUT to 120 mVpp. Verify that communications again work correctly.

Carrier Detect Start/Stop

This test requires a means of observing the actual Carrier Detect signal within the DUT (preferred) or at least a means of setting the non-DUT device to signal with only 3 preambles.

1. Start the communications software in the PC/Modem and the DUT. Set the HART signal amplitude into the DUT to 130 mVpp.
2. If you can observe the Carrier Detect signal in the DUT and the HART signal into the DUT, measure the time delay from the start of carrier to the active transition of the Carrier Detect signal. It should be less than 6 bit times i.e. less than 5 ms.
3. If the Carrier Detect signal in the DUT cannot be observed, set the PC software to only use 3 preambles in its messages to the DUT. If communications between the PC emulation and the DUT work properly, the Carrier Detect start-up in the DUT is adequately verified.
4. Set the HART signal amplitude into the DUT to the attainable maximum by adjusting the reference modem.
5. If the Carrier Detect signal in the DUT and the HART signal into the DUT are observable, measure the time delay from the end of carrier to the inactive transition of the Carrier Detect signal. It should be less than 6 bit times (i.e., less than 5 ms).
6. If the DUT is a slave and you cannot observe the Carrier Detect signal in the DUT, measure the time from the end of carrier of the master request to the end of carrier of the slave response. If this timing meets the data link layer timing requirements (256.7 ms + the calculated response length), the Carrier Detect Stop requirement in the DUT shall be considered to meet the specification.
7. If the DUT is a Primary Master and the Carrier Detect signal cannot be observed in the DUT, this test may be disregarded. The arbitration requirements of a HART network do not rely on the inactive transition of Carrier Detect in a Primary Master.

13.9.5 Notes Regarding Carrier Detect

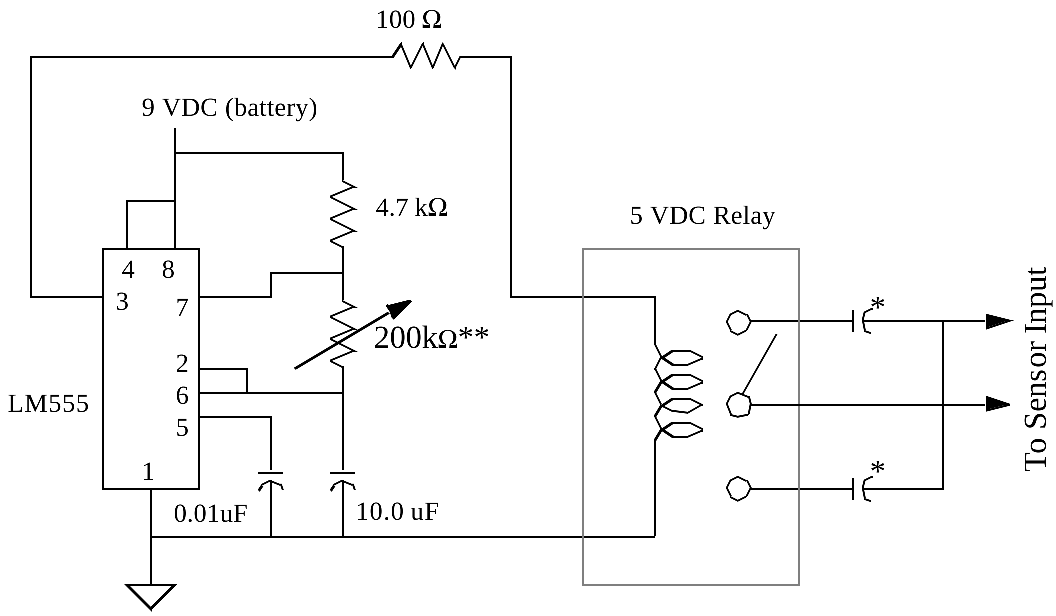
1. In observing HART communications with an oscilloscope to see if the DUT replies to a command that has been asserted, it is best viewed with an oscilloscope that has a ‘roll mode’ feature in its time base.

APPENDIX A. TEST CIRCUITS

A1. Simulated Sensor Circuit Suitable for Analog Rate of Change Test

The circuit below is a method for changing the stimulus to a device. In most HART applications where devices are designed to signal with the analog current, they respond to a change in input as measured by a sensor. The analog rate of change test requires the DUT to vary its input as fast as it is designed for the process it is exposed to and measure the rate at which the analog signal changes. In practice, it is difficult to change a sensor from zero to full scale, at maximum rates, in a lab environment. In most cases, a simulated sensor of some type is the most practical method of performing the test.

The simulated sensor can be done many ways, such as with a computer controlled analog multiplexer.



* Relay can switch between capacitance, resistance, voltage, or frequency to emulate a zero - full scale process change.

** Potentiometer used to adjust frequency from 0 -3 seconds

The above circuit used to activate switch between the different sensor elements can also be implemented with a computer, multiplexor card, and test software.

Figure 71. Simulated Sensor

A2. HCF Tools – Filter Characteristics

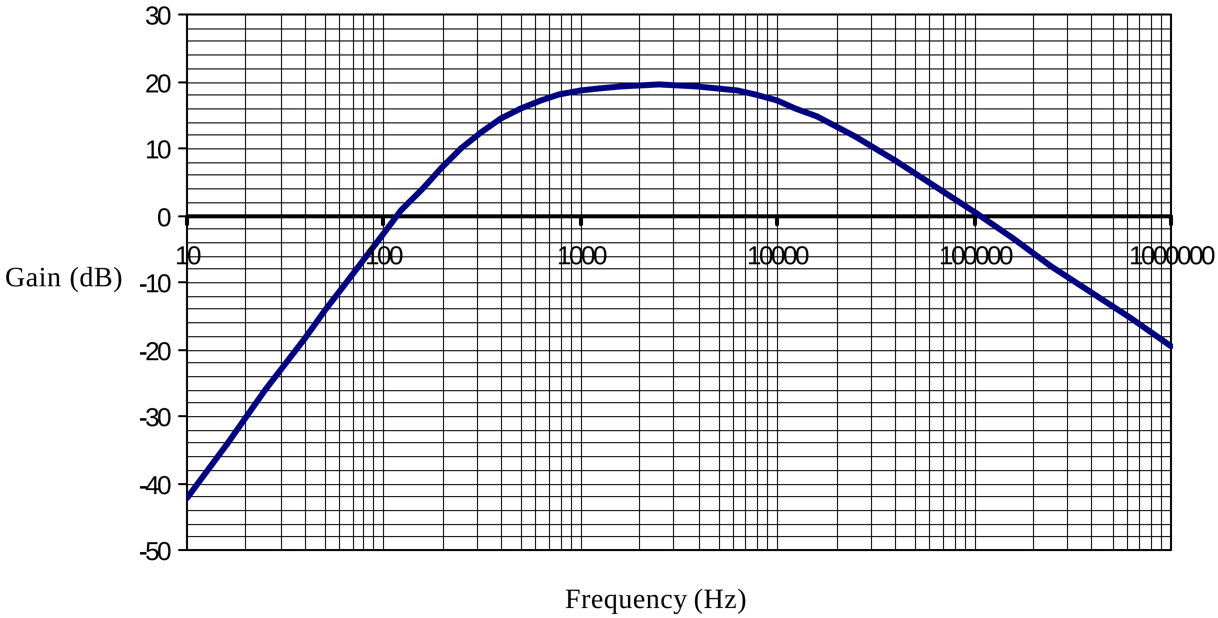


Figure 72. Band-Pass Filter Frequency Response, HCF_TOOL-31

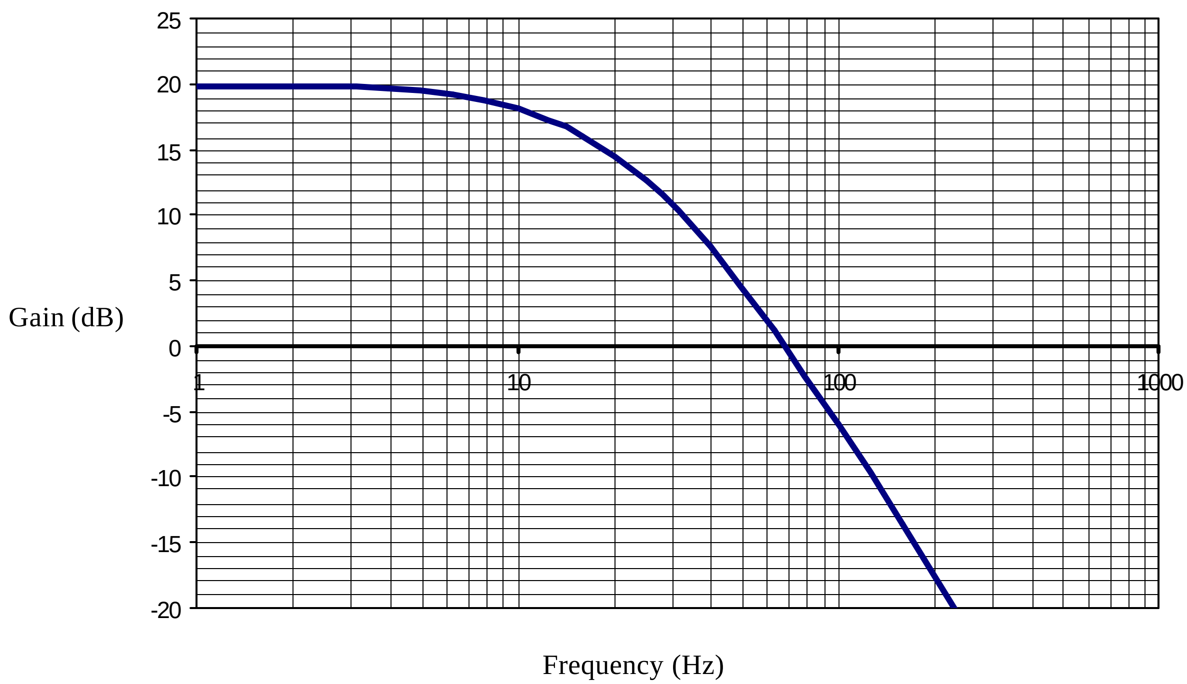


Figure 73. Low-Pass Filter Frequency Response, HCF_TOOL-32

APPENDIX B. BIPOLAR POWER SUPPLIES

For two of the conformance tests (impedance and the noise sensitivity tests), a power supply is required that has the ability to superimpose AC signaling on top of the DC network loop voltage. A commercially available supply manufactured by KEPCO[8] in conjunction with a common frequency generator, can supply the desired AC signaling on a DC voltage.

.

Table 18. Recommended Bipolar Power Supply Electrical Characteristics

Voltage	Current	Voltage Closed Loop Gain	Current Closed Loop Gain	Voltage Mode Impedance	Current Mode Impedance
+/- 50 VDC	+/- 2 Amp	5.0 V/V	0.2 A/V	0.5 mΩ 100 uH	50 kΩ 0.05 uF

Table 19. Recommended Bipolar Power Supply Electrical Characteristics

Mode	Bandwidth	Rise/Fall Time	Slew Rate (minimum)
Voltage	18 kHz	20 µs	5V/µs
Current	12 kHz	30 µs	0.15A/µs

8. KEPCO is a manufacturer of power supplies. KEPCO model number BOP-100-1M has been used successfully for the tests outlined in this document. There may be other manufacturers of power supplies that will meet the above listed recommendations as well.

APPENDIX C. TEST DATA SHEETS

The manufacturer must insure that specified device HART performance is met under all rated operating conditions. Optional tests at the extreme test conditions should be performed to insure compliance throughout the operating range.The following data sheets are the recommended forms for recording the Physical Layer test results.

Test Device:____ S/N ____________

Hardware Revision:_______________________ Software Revision: ____________________

Manufacturer: ____

Test Operator: __________________________ Test Date: _________________________

Device designed to meet HART Physical Layer Specification: ❑7.2 ❑8.0 ❑8.1

Physical Device Type:
❑ Current Input
❑ Current Output
❑ Voltage Input
❑ Voltage Output
❑ Secondary
❑ Transmitter
❑ Actuator
❑ Non-DC Isolated Bus Device
❑ DC Isolated Bus Device

Impedance Type:
❑ High Impedance
❑ Low Impedance

Does this product require any special configuration settings or installation techniques for the device to pass the all the physical layer tests? If so, these must be included in the product's user documentation.

❑ Yes, All special configuration and installation requirements are included in product's user documentation.

❑ No

Does your company plan to publish R_X and C_X impedance values in your end user product manual?

❑ Yes

❑ No plans on inclusion in manual

C1. Physical Layer Test Summary

100% pass of tests for HART Compliance is required. The following test summary must be included in submission of test results.

Table 20. Test Summary

Section	Test Name	Pass / Fail
13.1	Waveshape	❑ **PASS** ❑ **FAIL** ❑ **N/A**
13.2	Carrier Start / Stop	❑ **PASS** ❑ **FAIL** ❑ **N/A**
	Carrier Decay Timing	❑ **PASS** ❑ **FAIL** ❑ **N/A**
13.3	Carrier Start / Stop Transient	❑ **PASS** ❑ **FAIL** ❑ **N/A**
13.4	Output Noise During Silence	❑ **PASS** ❑ **FAIL** ❑ **N/A**
13.5	Analog Rate of Change	❑ **PASS** ❑ **FAIL** ❑ **N/A**
13.6	Receive Impedance Measurement	
	High Impedance:	R_X = ________ C_X= ________
	Low Impedance:	R_X = ________ C_X= ________ ❑ **PASS** ❑ **FAIL** Delta Z = ______ ❑ **PASS** ❑ **FAIL or** ❑ **N/A**
	Secondary:	Zm = ________ ❑ **PASS** ❑ **FAIL**
13.7	Send Impedance	❑ **PASS** ❑ **FAIL** ❑ **N/A**
13.9	Carrier Detect Level	❑ **PASS** ❑ **FAIL** ❑ **N/A**
	Carrier Detect Start / Stop	❑ **PASS** ❑ **FAIL** ❑ **N/A**
13.8	Noise Sensitivity	❑ **PASS** ❑ **FAIL** ❑ **N/A**

HART Physical Layer Conformance Data Sheet

C2. Waveshape

Test description can be found in Section 13.1 on page 41.

Transmit waveform @ 1200 Hz:

Insert Oscilloscope Picture Here

Measured Frequency: ______________ Hz (1188-1212 Hz) ❑ **PASS** ❑ **FAIL**

Measured Amplitude: ___________ mVpp

(400-800 mVpp; Lo Z) ❑ **PASS** ❑ **FAIL** ❑ **NA**

(400-600 mVpp; Hi Z) ❑ **PASS** ❑ **FAIL** ❑ **NA**

Measured Value of Current Sense Resistor: ____________Ω

Waveform Rise Time Characteristics: ____________(75 - 200 µs) ❑ **PASS** ❑ **FAIL**

Waveform Fall Time Characteristics: ____________(75 - 200 µs) ❑ **PASS** ❑ **FAIL**

HART Physical Layer Conformance Data Sheet

Waveshape (Continued)

Transmit waveform @ 2200 Hz:

Insert Oscilloscope Picture Here

Measured Frequency: ___________ Hz (2178-2222 Hz) ❑ **PASS** ❑ **FAIL**

Measured Amplitude: ___________ mVpp

(400-800 mVpp; Lo Z) ❑ **PASS** ❑ **FAIL** ❑ **NA**

(400-600 mVpp; Hi Z) ❑ **PASS** ❑ **FAIL** ❑ **NA**

Measured Value of Current Sense Resistor: ____________Ω

Waveform Rise Time Characteristics: ____________(75 - 100 µs) ❑ **PASS** ❑ **FAIL**

Waveform Fall Time Characteristics: ____________(75 - 100 µs) ❑ **PASS** ❑ **FAIL**

HART Physical Layer Conformance Data Sheet

C3. Carrier Start/Stop/Decay

Test description can be found in Section 13.2 on page 46.

Carrier Start Waveform:

Insert Oscilloscope Picture Here

Measure Carrier Start Time: ____________ (< 5 bit times, 4.2 ms) ❑ **PASS** ❑ **FAIL**

HART Physical Layer Conformance Data Sheet

Carrier Start/Stop/Decay (Continued)

Carrier Stop/Decay Waveform:

Insert Oscilloscope Picture Here

Measure Stop Time: _________ (< 3 bit times, 2.5 ms) ❑ **PASS** ❑ **FAIL**

Measure Decay Time: _________ (< 6 bit times, 5.0 ms) ❑ **PASS** ❑ **FAIL**

HART Physical Layer Conformance Data Sheet

C4. Carrier Start/Stop Transient

Test description can be found in Section 13.3 on page 51.

Carrier Start Transient Waveform:

Insert Oscilloscope Picture Here

Output of Test Filter :

2-pole Filter Output: __________ (100mV max*) ❑ **N/A**

(* The 100 mV test criteria includes the filter gain of 10)

❑ **PASS** ❑ **FAIL**

HART Physical Layer Conformance Data Sheet

Carrier Start/Stop Transient (Continued)

Carrier Stop Transient Waveform:

Insert Oscilloscope Picture Here

Output of Test Filter:

2-pole Filter Output: __________ (100mV max *) ❑ **N/A**

(* The 100 mV test criteria includes the filter gain of 10)

❑ **PASS** ❑ **FAIL**

HART Physical Layer Conformance Data Sheet

C5. Output Noise During Silence

Test description can be found in Section 13.4 on page 55.

The noise test is performed with an oscilloscope and a DVM. Oscilloscope picture (no filtering allowed with oscilloscope) of noise is required for the broadband test only.

Unfiltered Broadband Output Noise Waveform:

Insert Oscilloscope Picture Here

Broadband noise without a filter:

Output Noise =___________mV RMS (138 mV RMS Max.) ❑ **PASS** ❑ **FAIL**

In-band (500Hz-10 kHz) noise using HCF Digital Test Filter:

Output Noise =___________mV RMS (22 mV RMS Max.*) ❑ **PASS** ❑ **FAIL**

(* The 22 mV RMS test criteria includes the filter gain of 10)

❑ No filter was used (note 3) as outlined in Section 13.4.4 on page 57.

Notes:

1. In-band noise test is not required when broadband noise (no filter is used) is less than 2.2 mV RMS.

HART Physical Layer Conformance Data Sheet

C6. Analog Rate of Change

Test description can be found in Section 13.5 on page 59.

Analog Signaling Waveform:

Insert Oscilloscope Picture Here

Test device's A/D sampling rate: ____________ Hz

Test device's worst case sensor range-down: _____________

Test device's damping setting (minimum setting if applicable): ________________

Analog signaling filtered signal magnitude: _____________ mVpp (150 mVp max. *)

(* The 150 mVp test criteria includes the filter gain of 10)

❑ **PASS** ❑ **FAIL** ❑ **N/A**

Communication errors during analog signaling (100 communication attempts):

____________ / 100 ❑ **PASS** ❑ **FAIL** (0/100 required for a PASS)

HART Physical Layer Conformance Data Sheet

C7. Device Receive Impedance Data

Test description can be found in Section 13.6 on page 63.

High Impedance and Low Impedance Devices:

Table 21. High & Low Impedance Data

Case connect to (+) terminal				Case connect to (-) terminal			
Frequency	**V_a**	**V_b**	**Z_m****	**Frequency**	**V_a**	**V_b**	**Z_m****
200 Hz*				200 Hz*			
500 Hz				500 Hz			
950 Hz				950 Hz			
1.6 kHz				1.6 kHz			
2.5 kHz				2.5 kHz			
5 kHz				5 kHz			
10 kHz				10 kHz			
20 kHz*				20 kHz*			
50 kHz*				50 kHz*			

* Outside the HART Extended Frequency Band. 20 kHz and 50 kHz data for Low Impedance devices, 200 Hz data for High Impedance devices.

Note: Test requirements are for determining the impedance in the Normal Frequency Band. Data is recorded outside the Normal Frequency Band to calculate the variance of impedance for low impedance devices as well as providing additional data points when graphically determining the values for R_X and C_X for high impedance devices.

$$^{**}\ Zm = \frac{Vb \times R}{Va}$$

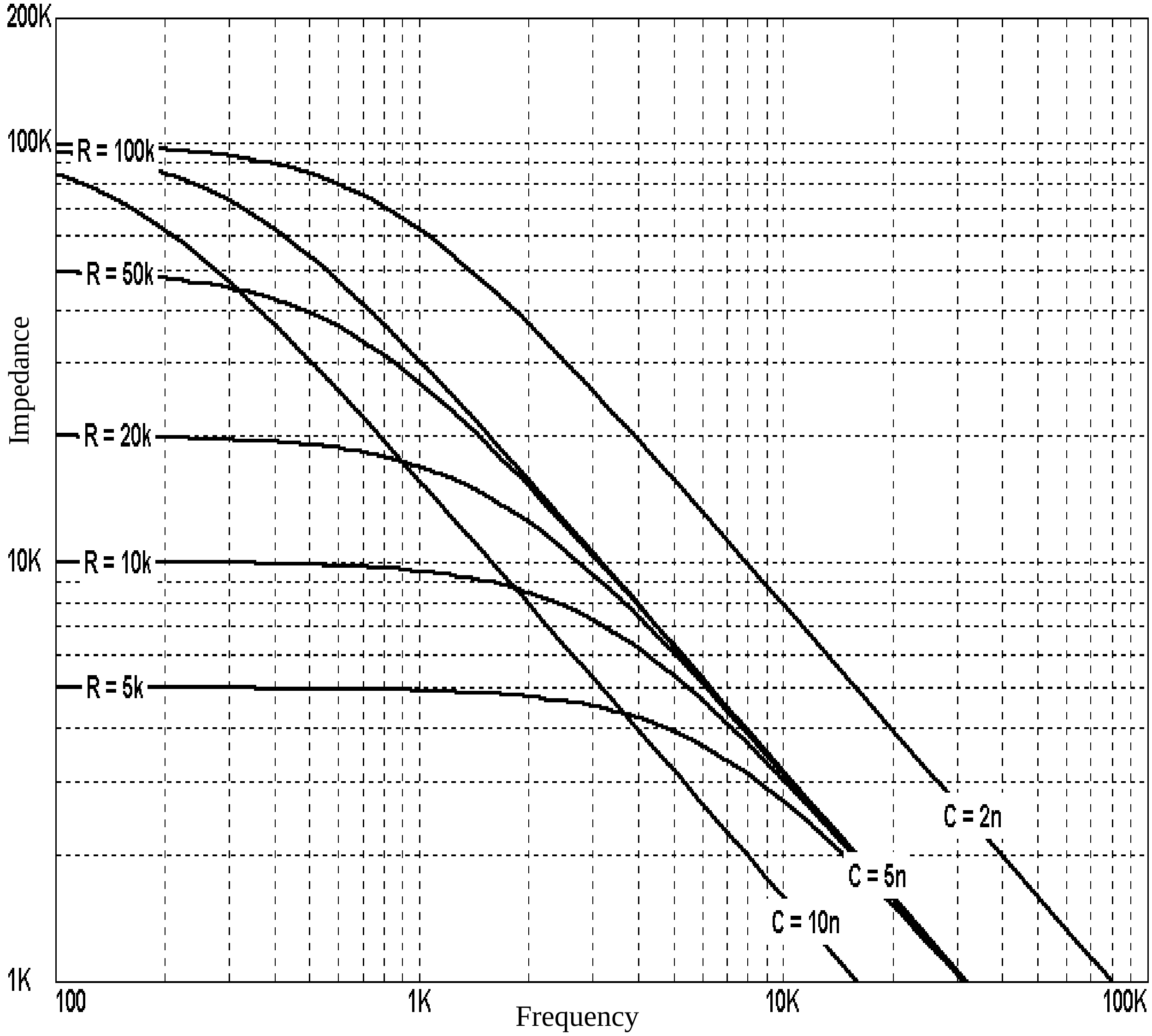
R = 5000 Ω for a High Impedance Device
R = 250 Ω for a Low Impedance Device

Is device ground-referenced?

❑ No

❑ Yes; Nature of ground reference: ____

High Impedance Magnitude Graph:



<u>High Impedance Devices</u>

1. Published R_X and C_X estimated from Impedance Magnitude data:

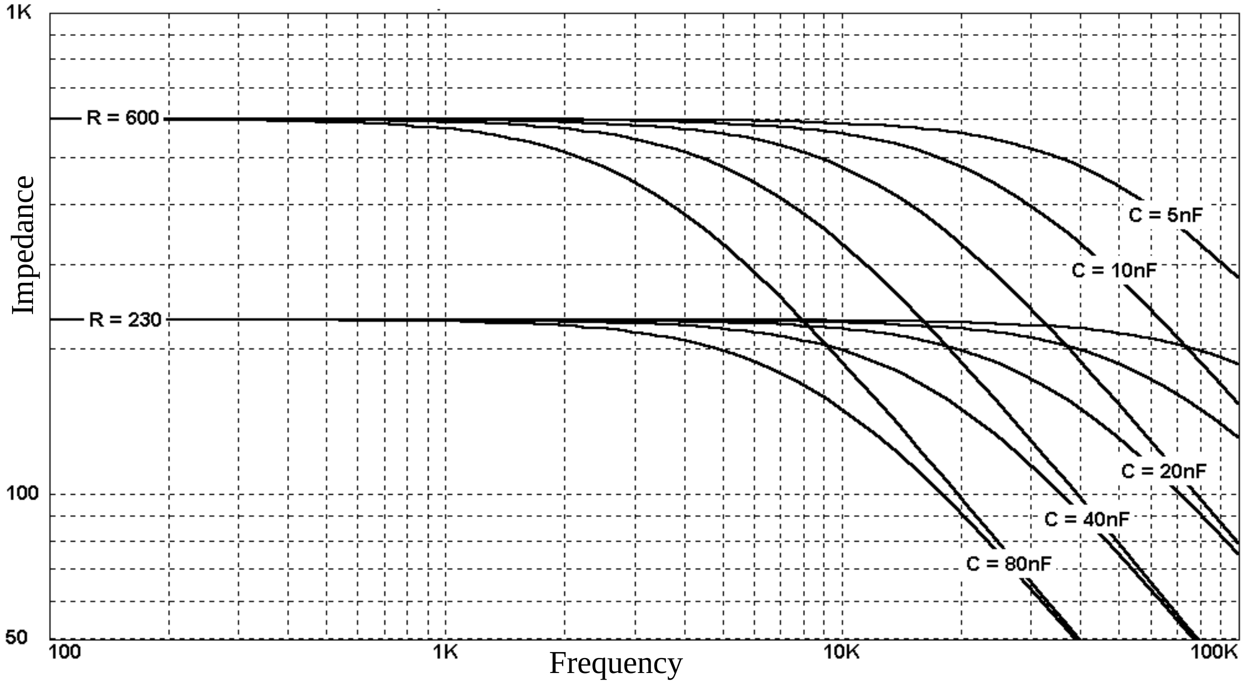
R_X: ________ Ω; C_X: _________ pF

2. Typical multidrop current ________ mA; ❑ NA, Device does not do multidrop

3. Non-Powered Measurements: R_{tg} (+) = __________; C_{tg} (+) = ____________

❑ NA R_{tg} (-) = __________; C_{tg} (-) = ____________

Low Impedance Magnitude Graph:



Low Impedance Devices

1. Minimum Receive Impedance, Zin, from Figure 21 (500 -10,000 Hz): _____________Ω

2. Maximum Receive Impedance, Zin, from Figure 21(500 -10,000 Hz): _____________Ω

3. Maximum Impedance / Minimum Impedance = _________ (spec = +/- 3 dB; i.e < 2)

❑ Pass ❑ Fail ❑ NA

4. Minimum Receive Impedance, Zin, from Figure 21 (950 -2500 Hz): _____________Ω

5. Maximum Receive Impedance, Zin, from Figure 21 (950 -2500 Hz): _____________Ω

230 Ω < Zin < 600 Ω ❑ Pass ❑ Fail

6. Published R_X and C_X estimated from Impedance Magnitude data:

R_X: ________ Ω; C_X: _________ pF

7. Non-Powered Measurements: R_{tg} (+) = __________; C_{tg} (+) = ____________

❑ NA R_{tg} (-) = __________; C_{tg} (-) = ____________

Secondary Devices:

Table 22. Secondary Impedance Data; Powered

Powered - Normal Polarity				**Powered - Reverse Polarity**			
Frequency	V_a	V_b	Z_m	**Frequency**	V_a	V_b	Z_m
950 Hz				950 Hz			
1.6 kHz				1.6 kHz			
2.5 kHz				2.5 kHz			

Table 23. Secondary Impedance Data; Device Off

Device Off - Normal Polarity				**Device Off - Reverse Polarity**			
Frequency	V_a	V_b	Z_m	**Frequency**	V_a	V_b	Z_m
950 Hz				950 Hz			
1.6 kHz				1.6 kHz			
2.5 kHz				2.5 kHz			

Secondary Devices

(note: Data must be recorded for forward and reversed polarity connection)

1. Minimum Receive Impedance, Z_m, all configurations, 950 Hz - 2.5 kHz: ____________ Ω

❑ Pass ❑ Fail (specification > 5 kΩ)

2. Non-Powered Measurements: R_{tg} (+) = ___________; C_{tg} (+) = _____________

❑ NA R_{tg} (-) = ___________; C_{tg} (-) = _____________

HART Physical Layer Conformance Data Sheet

C8. Send Impedance – Low Impedance and Secondary Devices

The calculated send impedance as outlined in Section 13.7.4 (using the 1.2 and 2.2 kHz data)

Secondary Device:

Test Load	Frequency	V1 (measured)	V2 (measured)	Calculated Impedance, Zout
500 Ω	1200 Hz		N/A	________ Ω*
230 Ω	1200 Hz	N/A		❑ PASS ❑ FAIL
500 Ω	2200 Hz		N/A	________ Ω*
230 Ω	2200 Hz	N/A		❑ PASS ❑ FAIL

* Test Criteria: (Send Zout x 0.80) < Receive Zin

Secondary Receive Impedance, Zin: ____________ Ω (from previous section)

Actuator Device:

Test Load	Frequency	V1 (measured)	V2 (measured)	Calculated Impedance, Zout
5k Ω	1200 Hz		N/A	________ Ω*
1k Ω	1200 Hz	N/A		❑ PASS ❑ FAIL
5k Ω	2200 Hz		N/A	________ Ω*
1k Ω	2200 Hz	N/A		❑ PASS ❑ FAIL

* Test Criteria: (Send Zout x 0.80) < Receive Zin

Actuator Receive Impedance, Zin: ____________ Ω (from previous section)

HART Physical Layer Conformance Data Sheet

Send Impedance (Continued)

<u>Current Input Device:</u>

Test Load	Frequency	V1 (measured)	V2 (measured)	Calculated Impedance, Zout
10k Ω	1200 Hz		**N/A**	________ Ω*
1k Ω	1200 Hz	**N/A**		❑ **PASS** ❑ **FAIL**
10k Ω	2200 Hz		**N/A**	________ Ω*
1k Ω	2200 Hz	**N/A**		❑ **PASS** ❑ **FAIL**

*Test Criteria: (Send Zout x 0.80) < Receive Zin

Current Input Receive Impedance, Zin: ____________ Ω

HART Physical Layer Conformance Data Sheet

C9. Noise Sensitivity Tests

Test description can be found in Section 13.8 on page 77.

Type of Interference	Frequency	Level	# of Errors (of 100 attempts)	Pass/Fail(Note 1)
In Band	1700 Hz	55 mVpp		❑ PASS ❑ FAIL
Out of Band	250 Hz	220 mVpp		❑ PASS ❑ FAIL
Out of Band	125 Hz	880 mVpp		❑ PASS ❑ FAIL
Out of Band	63 Hz	3.52 Vpp		❑ PASS ❑ FAIL
Out of Band	29 Hz	16 Vpp(Note 2)		❑ PASS ❑ FAIL

Note 1: No Allowable Errors

Note 2: A lower level of inject noise is allowable for Low Impedance Devices with integral current sense resistors (see note a on Table 11 of Physical Layer Specification Revision 8.1).

HART Physical Layer Conformance Data Sheet

C10. Carrier Detect Level

Test description can be found in Section 13.9 on page 82

Test Data:

Parameter	Signaling Amplitude (Note 1)	Pass/fail
Successful Error-Free Communications	120 mVpp	❑ **PASS** ❑ **FAIL**
Unsuccessful Communications	80 mVpp	❑ **PASS** ❑ **FAIL**
Successful Error-Free Communications	120 mVpp	❑ **PASS** ❑ **FAIL**

Note 1: If the 1200 and 2200 Hz signaling frequencies are of different amplitudes, the signaling level should be set using the signal of lesser amplitude.

Value of Current Sense resistor: ______________ Ω

Type of HART Modem used: _________________________________

Carrier Detect Start / Stop (Section 13.9 on page 82)

Direct Measurement - Using the carrier detect signal in the DUT's modem:

Start Time: __________ ms (< 6 bit times, 5 ms) ❑ **PASS** ❑ **FAIL** ❑ **N/A**

Stop Time: __________ ms (< 6 bit times, 5 ms) ❑ **PASS** ❑ **FAIL** ❑ **N/A**

Indirect Measurement - Carrier Start:

DUT responds to a message that has 3 preambles: ❑ **PASS** ❑ **FAIL** ❑ **N/A**

Indirect Measurement - Slave Carrier Stop:

Time between end of carrier of Primary Master's request to end of carrier of slave's response:

___________ ms (< 256.7 ms + response length) ❑ **PASS** ❑ **FAIL** ❑ **N/A**

APPENDIX D. REVISION HISTORY

D1. Changes from Revision 2.1 to 2.2

The document was modified from revision 2.1 to 2.2 to denote the insertion of the errata sheets at the front of the document. The change was made to correct the carrier transient test as outlined in the specification.;

D2. Changes from Revision 2.0 to 2.1

1. Grammatical errors corrected in Section 10.8.

2. Footnote numbering corrected throughout the entire document.

3. Section 13.3.1: text “10 mV” changed “100mV”.

4. Figures 24, 29, & 31: reference to 10x gain removed.

5. Section 13.3.4:

Removed last paragraph:

“To compute the average voltage under the previous requirement, the transientmust be integrated over the first 10 ms. For example, if thetransient is linear (although usually they are exponential), voltage may be as high as 100 mV, decaying to 0 mV after 10 ms.”

6. Section 13.3.5:

Removed paragraph 3:

“The Analog Test Filter has a gain of 10 to achieve a higher resolution of the measurement. The recorded data INCLUDES the gain factor such that the criteria of the test is adjusted to 100mV.”

7. Figure 30 updated with new picture showing RMS measurement.

8. Section 13.5.1, paragraph 1 and Section 13.5.4, paragraph 1: text “15mV” changed to “150mV”

9. Section 13.5.4; last paragraph:

Text “500” changed to “100”. (Same as noise testing. Using Command #1,
1 start char, 1 adr, 1 command, 1 byte count, 1 status, 5 data,
1chksum = 10,000 / (10 byte x 10 bit) = 100)

10,000 = bit error rate

10. 13.5.5, paragraph 2:

Entire paragraph added.

11. Figure 34: Changed axis and data by 10x.

12. Section 13.9.4, paragraph 2:

Deleted last sentence:

“If the HART signal at the terminals of the DUT is distorted (i.e. if the 1200 Hz and 2200 Hz signals are of significantly different amplitudes), a different modem may be necessary to obtain acceptable results.

(The test modem should NOT have different amplitudes)

13. Figures 46 & 47 updated.

14. C4, C5, & C6 Data Sheets updated.

15. Figures 37-40: axis labels added.

16. Errata typos: "ommitted" replaced with "omitted"

Character Start/Stop requirements:
"Timing with respect to 'characters' was inadvertently committed..." replaced with "Omitted"

17. Section 13.8.4, paragraph 2:
Text "For impedance devices." replaced with "For low impedance devices."

D3. Changes from Revision 1.1 to 2.0

Specification had been rewritten entirely.