HART Field Communications

Protocol Specification

HART® COMMUNICATION FOUNDATION

FSK Physical Layer Specification

HCF_SPEC-54, Revision 8.1

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ERRATA

This errata provides guidance for proper implementation of the HART FSK Physical Layer with respect to the 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 ommitted or relaxed in HCF_SPEC-54, Revision 8.1 and unfortunately, were not discovered prior to the specification release.

Device designers should use the following requirements for these parameters. FSK Physical Layer Specification Revision 8.2 will correctly state the requirements listed below and incorporate requirements important for the design of HART modem chips.

Carrier Stop/Carrier Decay Timing 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:

	Change from	Change to
Carrier Stop Time (RTS dissassertion to below 80mV)	5 bit times	3 bit times

Carrier Decay Time	Change from	Change to
(RTS dissassertion to carrier below maximum acceptable noise amplitude)	15 bit times	6 bit times

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 are reinstated as follows: (*Note*: definition has been modified to include Carrier Stop and Start time requirements)

Time from RTS assertion to First Character start bit:	5 bit times
Time from Last Character to Carrier OFF: (carrier below maximum acceptable noise amplitude)	11 bit times

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Preface

Revision 8.1 of the HART Physical Layer Specification (HCF_SPEC-54) has evolved from several previously released revisions (7.0, 7.1, 7.2., and 8.0). Revisions 8.0 and 8.1 differ from prior revisions in the following ways:

Device Names

New terms were developed to more closely represent the unique electrical properties of devices. References to ‘slaves’ and ‘masters’ throughout this document are now made only when describing devices with respect to the Data Link Layer.

Connection Types

Additional device connection types are permitted within a HART network.

Device Topologies

New HART network topologies have been incorporated to support the new device types.

Document Format

The document was reformatted to align more closely with IEC/ISO specifications.

A summary of changes is listed in Annex C of this document. Revision 8.1 differs from revision 8.0 as follows:

1. The upper impedance limit of a low impedance devices was adjusted from 1100 Ω to 600 Ω
2. Carrier Decay timing requirements were added.
3. Carrier Start/Stop transient requirements were tightened.
4. Section 7 was reformatted to improve definitions and relationships between the analog and digital signaling spectrum.
5. Methods in Section 7.5.3 for Calculating Single-Pair Cable Length were revised.

This standard was developed by the HART Communication Foundation Physical Layer Working Group. The intent of this specification is to define the electrical properties of HART devices and networks, to facilitate the design of related products.

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

NAME	COMPANY
Doug Arntson, Chairman, Editor	Rosemount Inc.
Kari Hartikainen	Neles-Jamesbury
Ulrich Hempen	Hartmann & Braun AG
Ed Miller	Southwest Research
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Introduction

The HART Protocol is a transaction-oriented communication service for process control devices. Designed to augment traditional 4-20 mA analog signaling, HART communicating devices provide relatively low-bandwidth, moderate response-time communication in industrial environments. Applications include remote process variable interrogation, parameter setting, and diagnostics.

HART digital signaling is an extension of conventional analog signaling. Using 1200 bps binary phase-continuous Frequency-Shift-Keying (FSK), a high frequency current is superimposed on a low-frequency (typically 4-20 mA) analog current. The two signals share much of the same hardware but differ in frequency. HART communicating devices signal with either current or voltage, and all signaling appears as voltage when sensed across a low impedance.

For purposes of convenience, communicating device are described in terms of Data Link and Physical Layers according to the OSI 7-Layer Communication Model [see Related Documents]. The Data Link Layer primarily specifies the HART protocol, while the Physical Layer specifies the signaling method, signal voltages, device impedances, and media. However, as regards hardware or software, no clear boundary exists between layers. Effectively, the division into layers should be viewed as a division into functions.

The Data Link Layer requires specific services of the Physical Layer. These services are described fully in the Data Link Layer Specification (HCF_SPEC-81).

The Physical Layer commonly uses twisted-pair copper cable as its medium and provides solely digital or simultaneous digital and analog communication. Maximum communication distances vary depending on network construction and environmental conditions. The Physical Layer requirements for HART communication are the focus of this document. An representation of the relationship between the HART protocol communications layers (including firmware and hardware) is given in Figure 1.

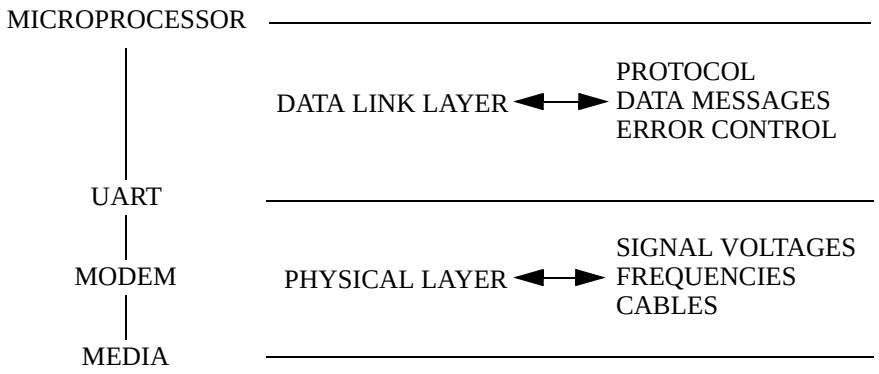


Figure 1. Data Link Layer and Physical Layer Relationship

1 SCOPE

The HART Physical Layer Specification provides information necessary to construct and use HART networks and devices. This document is devised to:

1. Promote interoperability among HART devices.
2. Supply guidelines for acceptable communication under a variety of conditions.
3. Provide guidelines for minimization of interference to and from 4-20 mA signaling.

2 NORMATIVE REFERENCES

2.1 Related HART Documents

1. HART Physical Layer Test Procedure, HCF_TEST-2.
2. HART Data Link Layer Specification, HCF_SPEC-81.

2.2 Related Communication Documents

1. ISO 7498-1984, Open Systems Interconnection – Basic Reference Model.
2. Bell System Technical Reference, PUB 41212, “Data Sets 202S and 202T Interface Specification,” July, 1976.
3. Appendix to Bell System Technical Reference, PUB 41004, “Data Communications Using Voiceband Private Line Channels,” October, 1973.

2.3 Other Related Documents

The HART protocol does not require compliance to the documents listed below. However, many HART devices are designed and tested to meet the requirements.

1. EN 50 081-1, European Standard, Electromagnetic Compatibility
2. EN 50 081-2, European Standard, Electromagnetic Compatibility
3. EN 50 082-1, European Standard, Electromagnetic Compatibility
4. EN 50 082-2, European Standard, Electromagnetic Compatibility

3 DEFINITIONS

Analog Controller — A conventional controller designed for use with only 4-20 mA signaling that meets all requirements of a current input device or current output device.

Analog Signaling — A low frequency signal (usually 4-20 mA) sent to or originating from a field device.

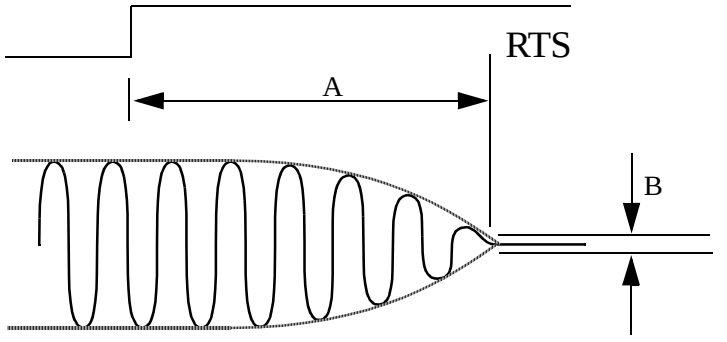
Analog Signaling Spectrum — The frequencies from DC to 25 Hz (with -40 dB per decade above 25 Hz).

Analog Test Filter — A filter (HCF_TOOL-32) designed to define the amount of energy a digital signaling device may generate from assertion or removal of its carrier (see Section 7.3.2.1) 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.

Cable Capacitance Per Unit Length — The capacitance per unit length of cable, measured at 1 kHz from one conductor (not including shield) to all others (including shield) combined. For networks comprised of more than one type or gauge of cable, the highest capacitance value of any cable type or gauge is used to determine this value.

Carrier Decay Time — Time from the disassertion of RTS until the carrier drops to an amplitude within the range of allowable noise (see Figure 2 below).



A = Carrier Decay Time B = Maximum Acceptable Noise Amplitude

Figure 2. Carrier Decay Time

Carrier Start Time Time from the assertion of RTS until the carrier reaches an acceptable amplitude (see Figure 3 below).

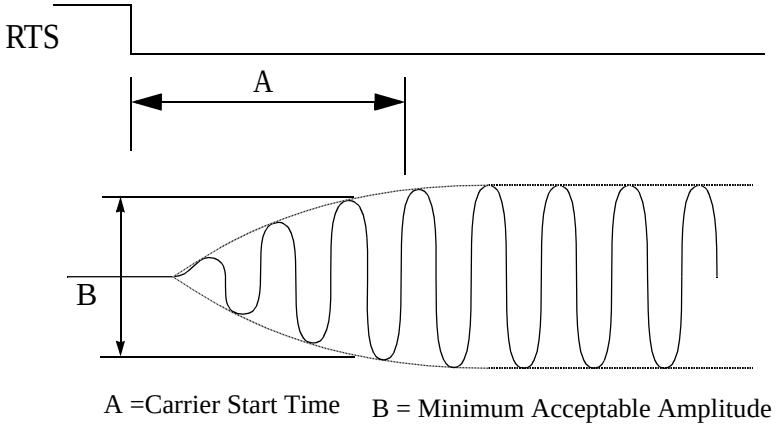


Figure 3. Carrier Start Time

Carrier Stop Time Time from the disassertion of RTS until the carrier drops to an unacceptable amplitude. This is illustrated in Figure 4 below.

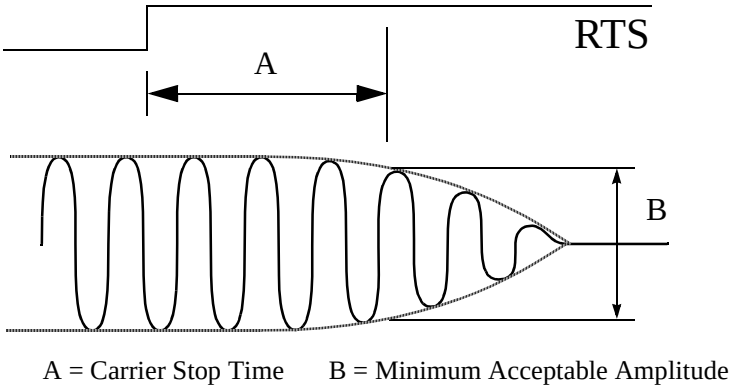


Figure 4. Carrier Stop Time

Current Sense Resistor A resistor that may be used to convert analog current signal to a voltage signal.

Delay Distortion The difference in time delays of sine waves of different frequencies when observing the time delay through a network or circuit.

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

The purpose of the Digital Test Filter (HCF_TOOL-31) is to define by the means of a filter, the amount of energy an analog signaling device may generate in the digital signaling spectrum.

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 is silence (see Figure 5).

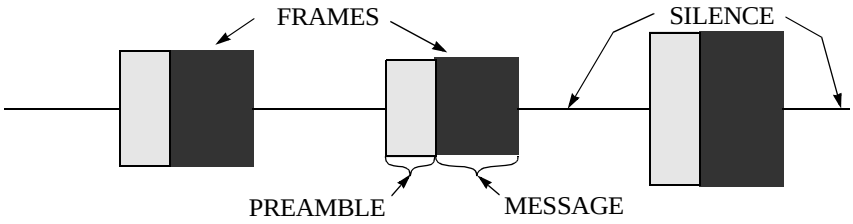


Figure 5. HART Digital Signaling Frames

Frame (Continued)

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 6. The parity will be true (1) if number of 1's in the data byte is even.

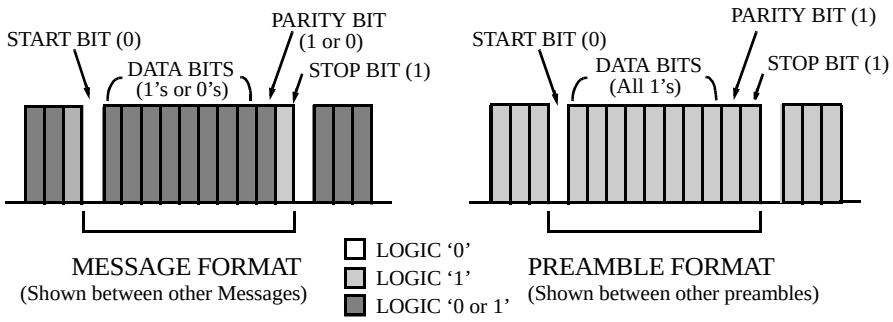


Figure 6. HART Byte Format

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.

Junction

Any splice of two cables or any attachment point of another cable or of a field device to an existing cable.

Message

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

Multi-Dropped Network

A Data Link Layer term for a network with more than one Slave Device.

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.
Point-to-Point Network	A Data Link Layer term for a network with one slave device.
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 five (5) preambles and a maximum of twenty (20) preambles.
Primary Master	A Data Link Layer term for a signaling element that initiates communication with one or more slave devices. 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 slave devices 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.

4 SYMBOLS AND ABBREVIATIONS

AWG	American Wire Gage
C_{Dev}	Device Capacitance
C_{tg}	Capacitance Terminal to Ground
C_{tt}	Capacitance Terminal to Terminal
C_X	Equivalent Device Capacitance
DUT	Device Under Test
EMI	Electro Magnetic Interference
FSK	Frequency Shift Keying
HART	Highway Addressable Remote Transducer
HCF	HART Communication Foundation
K_C	Cable Capacitance Per Unit Length
RMS	Root Mean Square
R_P	Parallel Network Resistance
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 PHYSICAL DEVICE TYPES

This section categorizes and specifies the properties of various physical connections to HART networks. In many cases, HART devices are capable of operating in more than one mode or exhibit characteristics of more than one connection type by changes in configuration. Therefore, this section is NOT intended to categorize *products* but rather *connection types*.

The primary distinction between devices is impedance level. All signaling elements can be classified as either low impedance or high impedance devices. Further distinctions are made on the basis of connection type and associated characteristics.

Frequently throughout this specification, reference will be made to devices by connection type or impedance class alone. A thorough discussion of physical parameters for all device types is the topic of Section 7, Common Characteristics of All Device Types.

5.1 Low Impedance Devices

Low impedance devices are typically signaling elements intended to receive analog current signaling or serve as the master for a multi-drop network. DC power considerations require current receivers (such as a controller analog input device or an actuator) be very low impedance at analog signaling frequencies. It is impractical for devices of this type to also have high impedance at HART frequencies. Since the maximum allowable cable length is provided with a low impedance, it is most convenient to make this device the dominant low impedance of the network.

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). However, designing devices to function at either extreme is unwise. At the low end of the range, the loop has little tolerance for parallel resistance. At the high end, the loop has less tolerance for wiring capacitance. Wire length calculations and specifications of other devices will serve as guides for designers to establish practical impedance.

To prevent signal distortion, the impedance of these devices is required to be ‘flat’ (i.e., the impedance remains within ± 3 dB of a constant value over the extended frequency band).

5.2 High Impedance Devices

High impedance devices control current, either as a means of analog signaling or at a fixed level in a multi-drop environment. In either case, these devices are naturally high impedance since accurate current control is high impedance by definition. By default, all devices that do not qualify as low impedance devices (230 Ω - 600 Ω) fall into the class of high impedance.

Generally, high impedance devices should be designed to have as high an impedance as practical within other design constraints. High impedance will allow the most devices to be connected in parallel without attenuating the HART signal. Transmitters, for example, usually have impedances >100 kΩ within the normal frequency band of 950 Hz - 2500 Hz. This allows several to be placed on a multi-drop network without appreciably reducing the signal. The exception to this convention is the secondary device type which has a minimum impedance of 5 kΩ.

It may be physically possible to design a functional transmitter with impedance as low as 1 kΩ under limited conditions. However, such a device would probably not be suitable in a multi-drop application and would certainly not function with even a single device whose impedance is in the lesser end of the low impedance range.

5.3 Device Connection Types

Communicating devices on a HART network may be of the following connection types. Any particular device may exhibit characteristics of more than one of these connection types.

1. Current Input (Formerly Primary Master)[1]
2. Current Output (Formerly Type C field device)
3. Voltage Input (New)
4. Voltage Output (Formerly Voltage Mode slave device)
5. Secondary (Formerly Secondary Master)
6. Transmitter (Formerly Type A or B slave device)
7. Actuator (New)
8. Non-DC Isolated Bus Device (Formerly Type A slave in multi-drop mode)
9. DC Isolated Bus Device (Formerly Type D field device).

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 1 below.

1. Former terms are referenced from those used in revision 7.2 of this document.

Table 1. Device Connection Characteristics

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

5.3.1 **Current Input** (Formerly Primary Master[1])

Current input devices (including sense resistor) have low impedance and are often not isolated from ground. The most common example of a current input device is the controller connection for an analog input loop (a loop with a common 4 - 20 mA transmitter as the field device).

Current input devices may incorporate the network power supply and provide DC power to the loop. They may alternatively rely on an external power supply. These devices will generally include internal current sense resistors or specify an externally connected sense resistor. In either case, the impedance of a current input device should be specified to include the current sense resistor. For a given device, if a range of sense resistance is specified, the device parameters should be specified as a function of the sense resistor value.

1. Former type name from revision 7.2

5.3.2 **Current Output** (Formerly Type C Field Device[1])

Current output devices are high impedance and always provide the analog signal to the loop. Usually these devices are not isolated from ground. Examples of current output devices are the controller connection for an analog output loop (a loop with a common 4 - 20 mA actuator or positioner as the field device) or a separately-powered field device that sources current to the loop rather than sinking it from the loop.

Current output devices may source current to the network by incorporating the network power supply, or they may connect in series with an external power supply and simply control the loop current.

5.3.3 **Voltage Input** (New)

Voltage input devices do not provide DC power to the loop, have a high impedance, and may or may not be isolated from ground. Examples are the controller connection for an analog input loop where the analog signal is voltage (e.g., from a voltage output transmitter) or a separately powered output device that accepts voltage as its analog input signal rather than current.

In order for this type of device to function, the DC impedance needs to be high enough that resistance in the loop does not introduce an error on the voltage signal. Because of the high DC impedance, voltage input devices are assumed to be high HART impedance as well.

5.3.4 **Voltage Output** (Formerly Voltage Mode Slave Device)

Voltage output devices do not provide DC power to the loop and are low impedance. They may or may not be isolated from ground. By controlling DC voltage, voltage output devices are assumed to be low impedance for HART signaling.

The most common example of this HART device is a 3-wire voltage output transmitter. Another example is a controller designed to drive a separately powered field device. A network with analog voltage signaling cannot carry DC power since this causes voltage drop in loop wiring and an unacceptable error in the analog signal.

5.3.5 **Secondary** (Formerly Secondary Master[1])

Secondary devices are always DC isolated from the current loop and high impedance. Any device that is intended as a removable connection, that is not required for communication on the loop, and is not included in the wire length calculations is considered a secondary device. The most common example of a HART secondary device is a handheld terminal or other type of temporary connection.

1. Former type name from revision 7.2

Network analysis calculations assume the presence of a secondary device on the network. Devices that do not qualify as secondary devices, but are intended for use as such, must be included in the network analysis calculations.

5.3.6 **Transmitter** (Formerly Type A or B slave device[1])

Transmitters draw DC current from the loop, vary the amount of current drawn as a means of analog signaling, are DC isolated from ground, and are high impedance. Examples of this HART device type are 2-wire transmitters or separately powered transmitters with loop interface that draw DC from the loop. The HART Protocol does not distinguish between devices that present the same electrical properties to the loop.

5.3.7 **Actuator** (New)

Actuators draw DC power from the loop at a current level determined by the current sourcing device. These devices are always DC isolated from ground and low impedance. The most common examples of actuators are 2-wire devices that receive an analog signal via 4 - 20 mA loop current supplied by a controller. A separately powered device with a loop interface that accepts DC from the loop like a 2-wire transmitter would also fall into this category.

5.3.8 **Non -DC Isolated Bus Device** (Formerly Type A slave in multi-drop mode[1])

Non-DC isolated bus devices normally draw a constant DC current from the loop but are not required to derive their power from the loop. They are usually DC isolated from ground and are usually high impedance. The most common example of this HART device is a 2-wire transmitter when in a fixed current mode.

5.3.9 **DC Isolated Bus Device** (Formerly Type D Field Device[1])

This device type includes independently-powered devices that connect to the loop for digital communication only. DC isolated bus devices will normally have high impedance. DC isolated bus devices may exist on any loop, including loops with analog signaling, since they do not effect the analog signal. Loops may be constructed with only this type of device, that is, loops with no DC current flowing at all.

1. Former type name from revision 7.2

6 NETWORK CONFIGURATION RULES

The rules outlined in this section are intended to regulate the physical properties of networks and ensure reliable signal transmission. These rules permit combinations and configurations of hardware not permitted by the Data Link Layer Specification or that may be prone to failure under DC power.

6.1 Definitions of Elements

Networks will consist of cable, communicating devices and non-communicating devices as specified in other sections of this document.

6.2 Combination of Elements

The following rules govern the combinations of elements on a HART network:

6.2.1 Rule Number 1

A network must have at least one, typically only one, low impedance device. The combined parallel impedance of all connected devices must fall in the range of 170 Ω - 600 Ω.

6.2.2 Rule Number 2

A network must have no more than one analog signaling device.

6.2.3 Rule Number 3

A network may have up to 16 devices[1] as allowed by the DC power limitations, the cable length calculation and the noise requirement.

6.2.4 Rule Number 4

Only one secondary device is allowed.

6.2.5 Rule Number 5

The cable length must be less than or equal to the maximum allowed by the cable length calculation (or graphical chart interpretation) for the combination of elements connected.

1. The maximum of 16 devices is derived by the noise calculation. A network may be constructed with more than 16 devices provided it meets the noise calculations of this specification. Network that exceed the limits defined by the noise calculation may have degraded communication performance.

6.3 Example Topologies

6.3.1 Point to Point Current Input

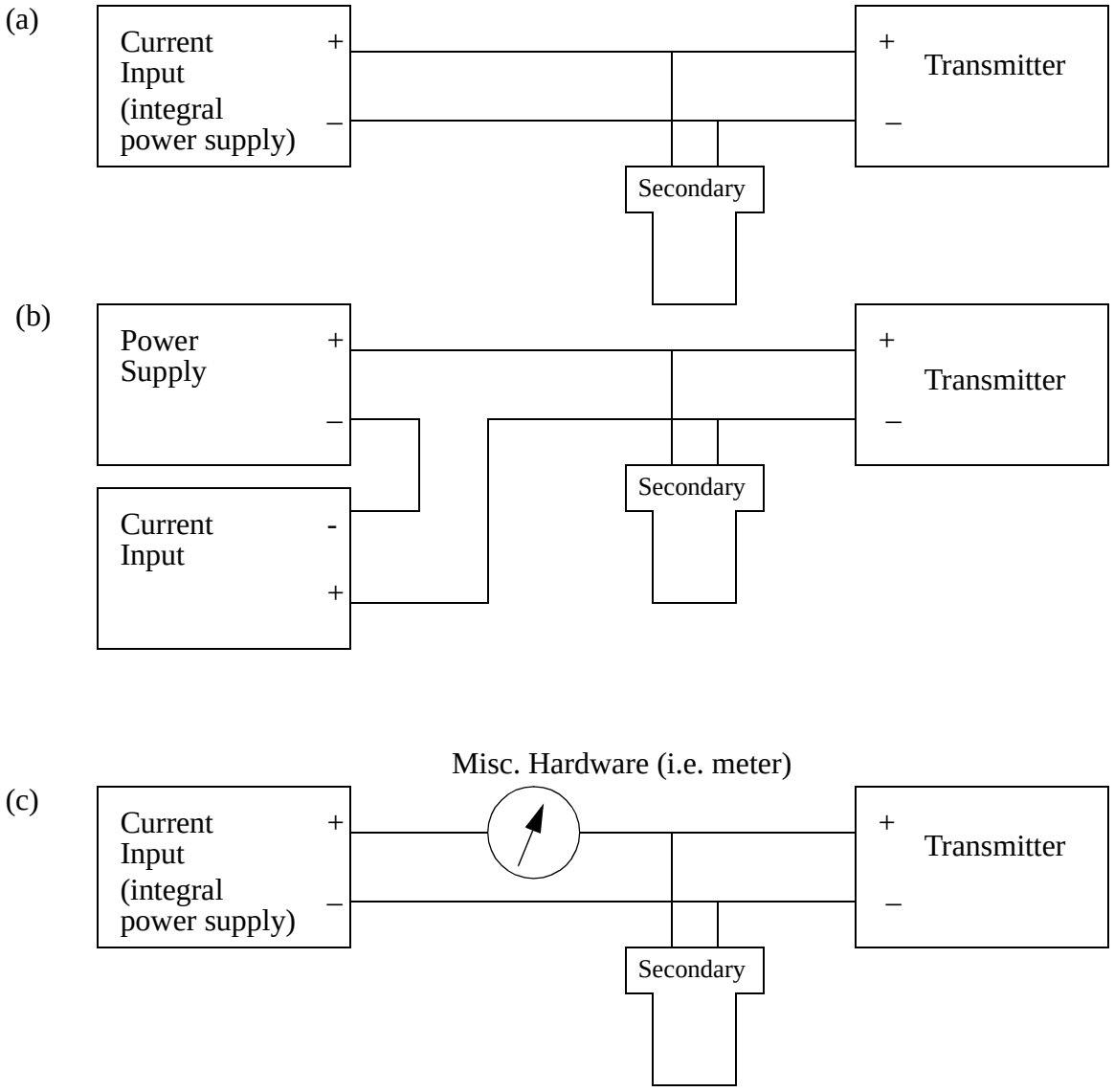


Figure 7. Point to Point Current Input Topology

6.3.2 Point to Point Current Output

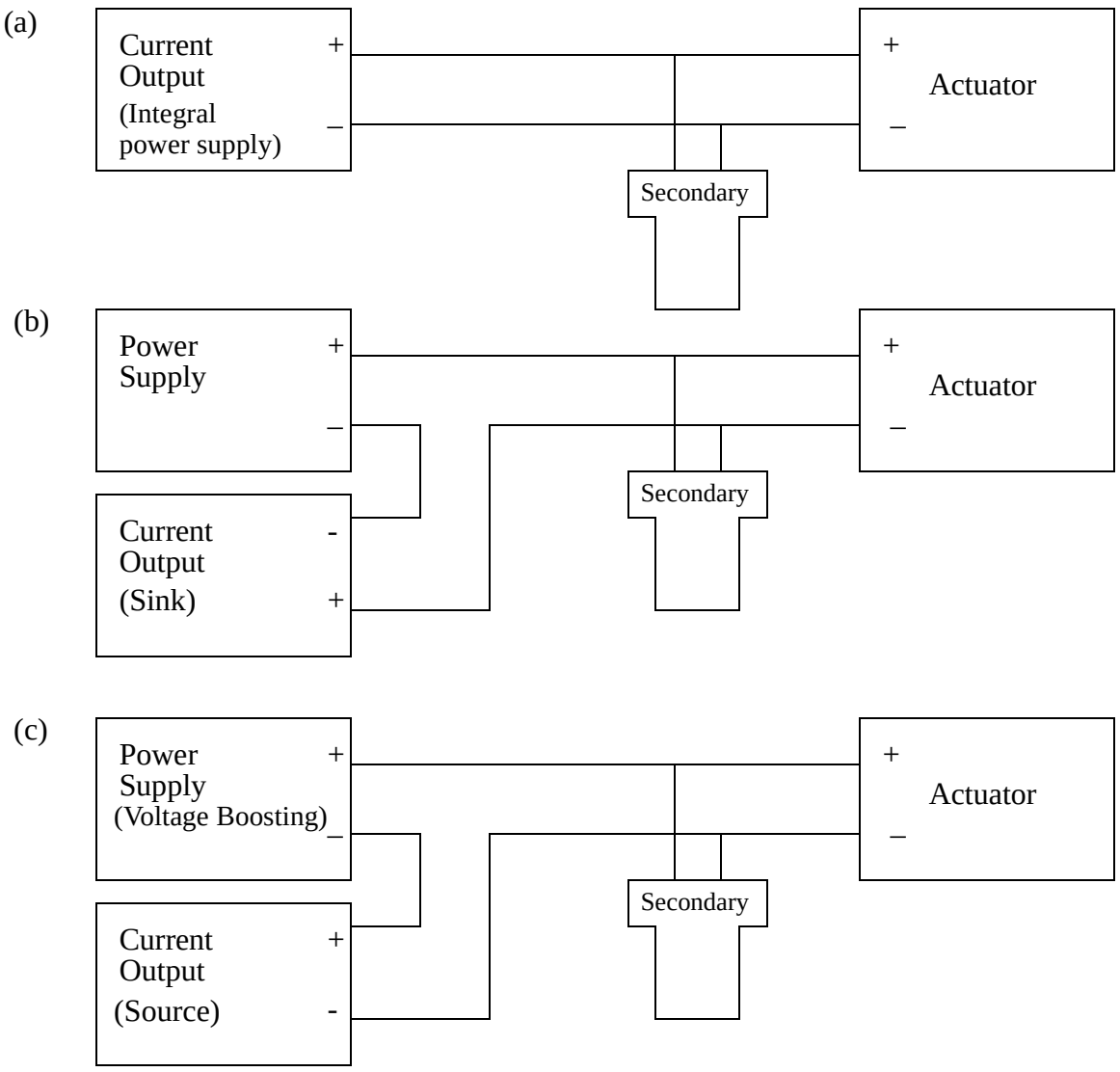


Figure 8. Point to Point Current Output Topology

6.3.3 Multi-drop

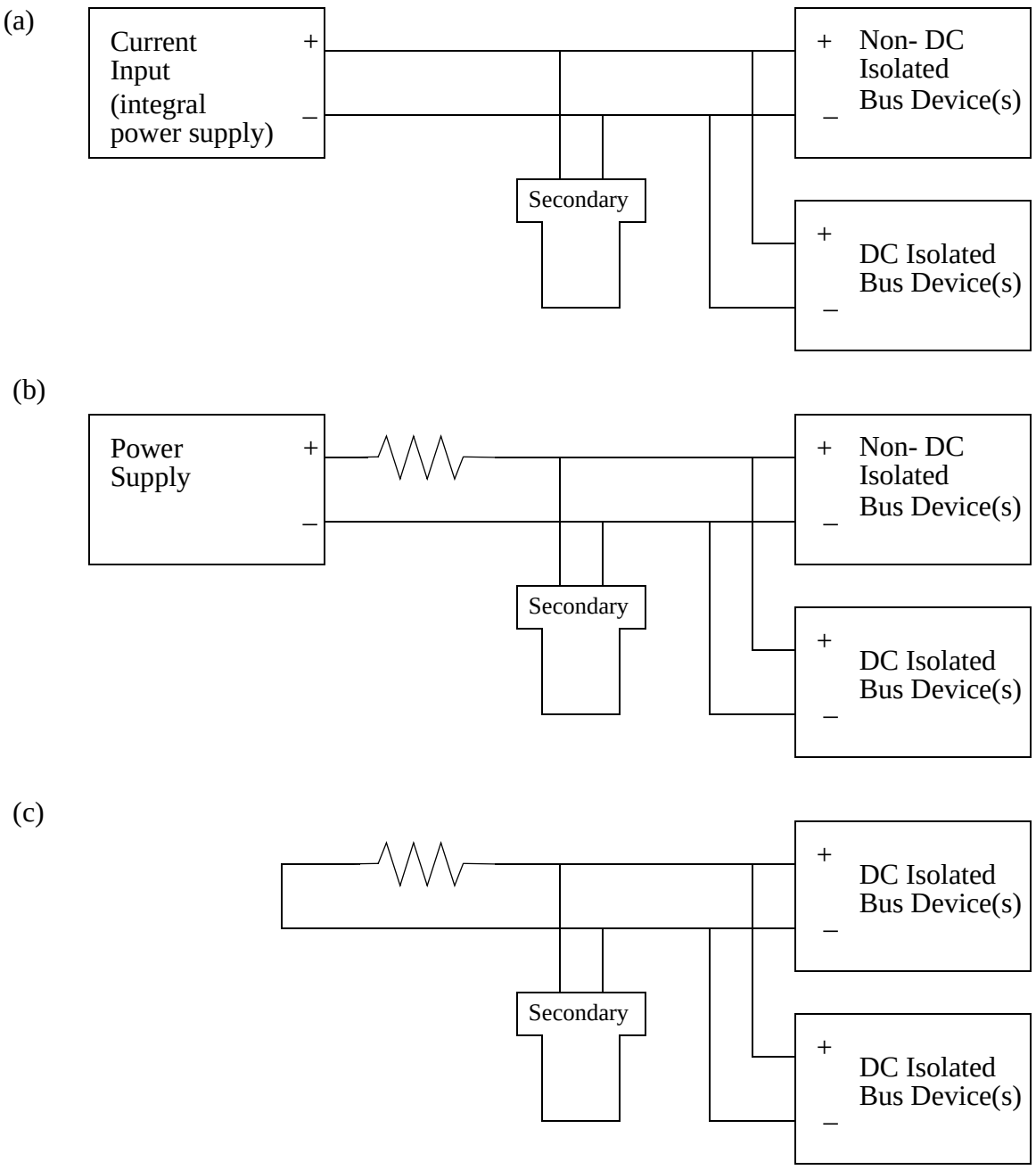


Figure 9. Multi-drop Topology

6.3.4 Multi-drop with Analog Signaling

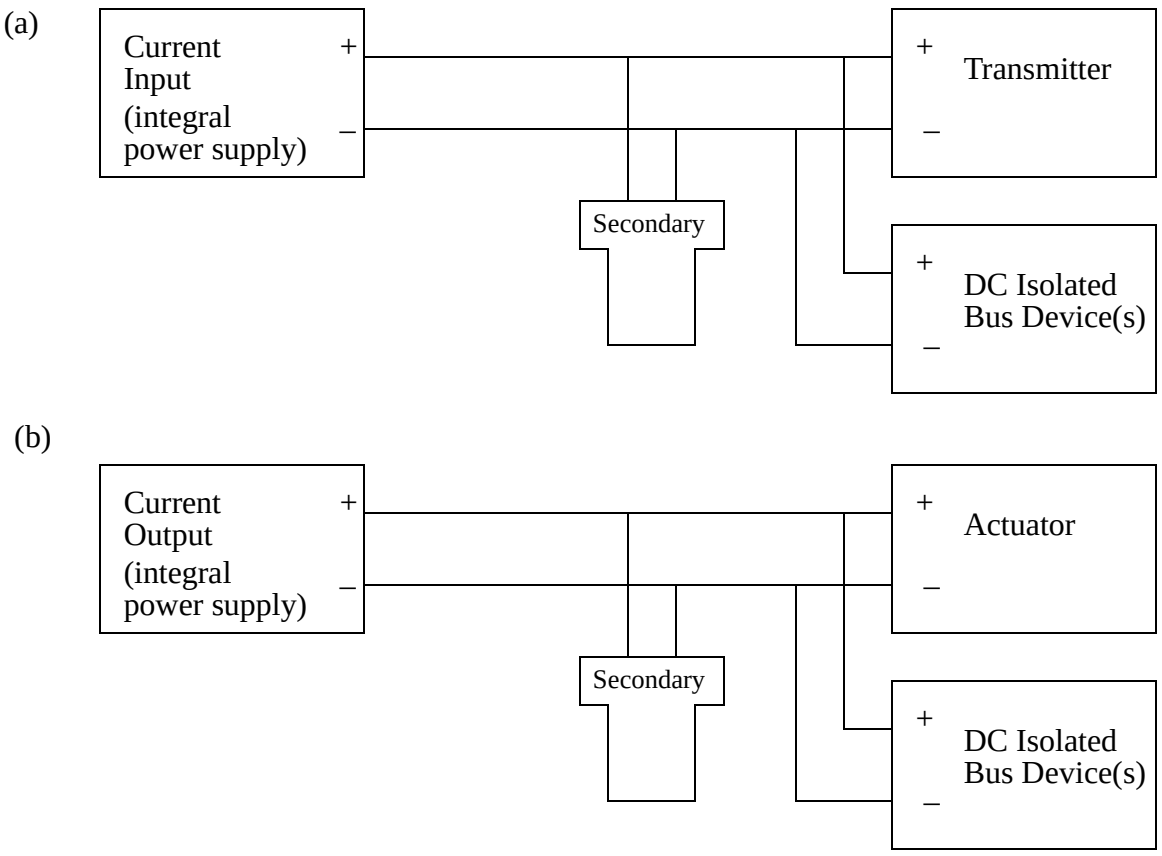


Figure 10. Multi-drop with Analog Signaling Topology

6.3.5 Series Connection

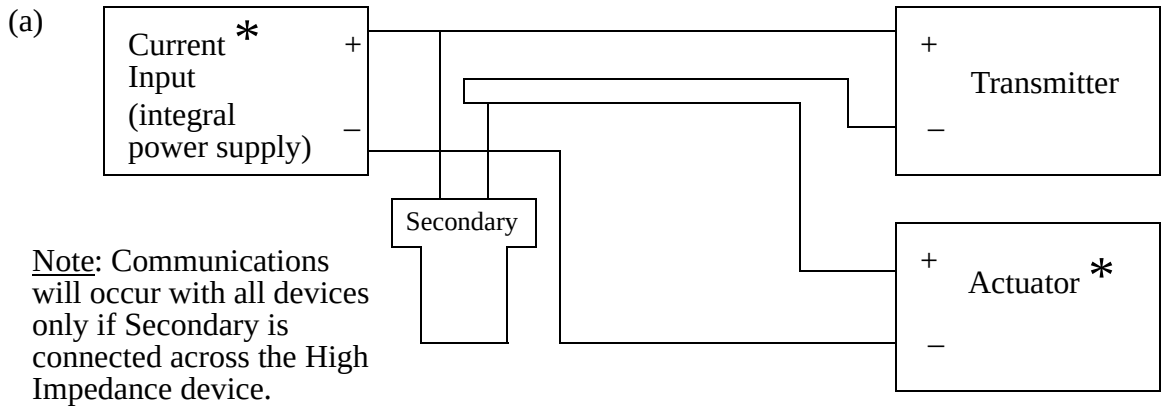
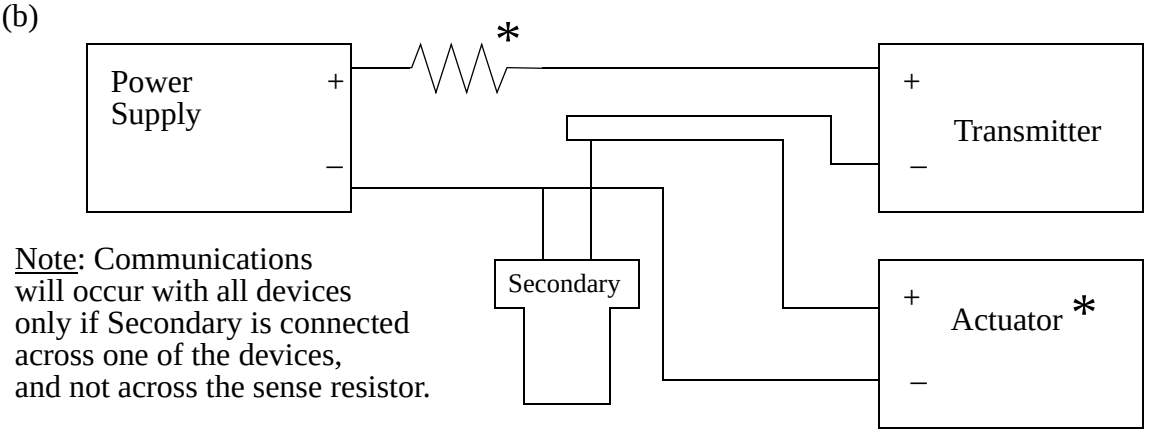
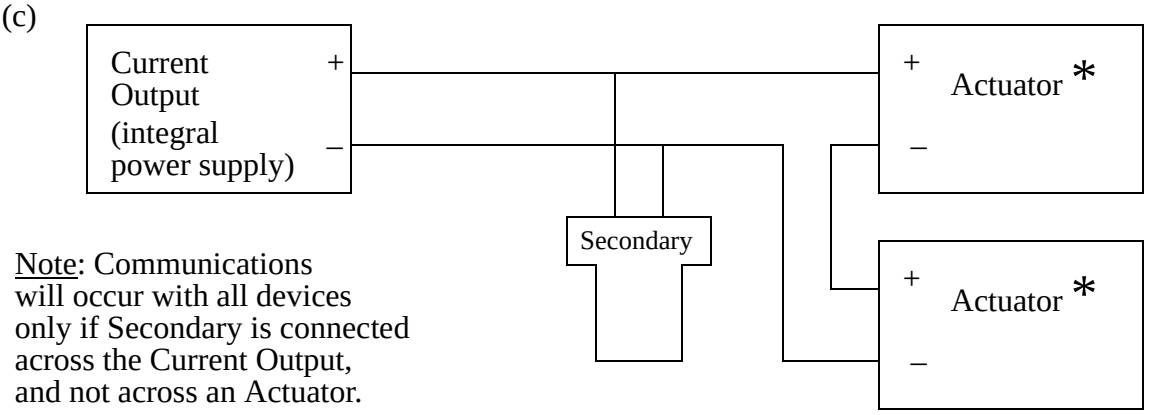


Figure 11. Series Connection Topology

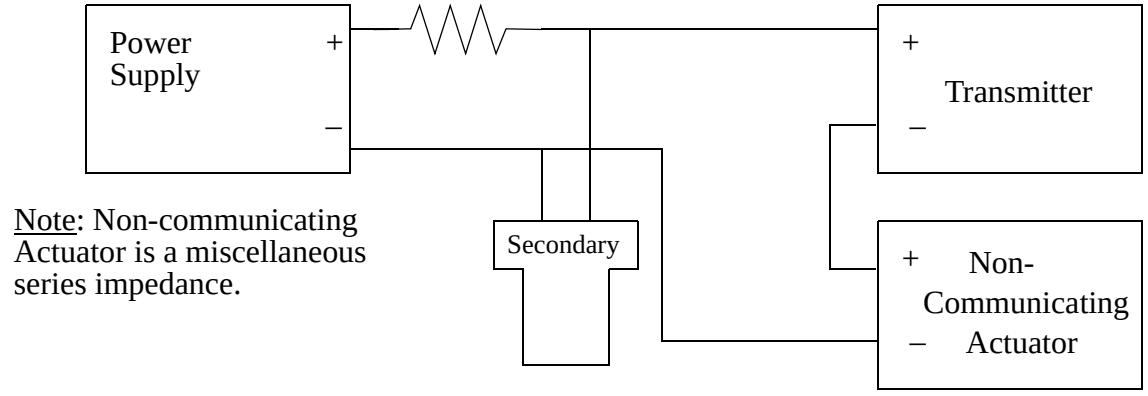
(b)



(c)



(d)



* Denotes impedance matching required to achieve optimum signaling lengths. Impedance matching is determined by analyzing the network according to section 7.5.3 for each low impedance device with the other low impedance device considered as series impedance.

Figure 11. Series Connection Topology (continued)

7 COMMON CHARACTERISTICS OF ALL DEVICE TYPES

Common characteristics are electrical requirements, test parameters, and cable limitations imposed on all devices. Adherence to the listed specifications will insure that all conforming devices on a HART network will properly communicate and not interfere with other devices.

7.1 Digital Signaling Requirements

The requirements for digital signaling have been defined to ensure digital communication under specified conditions is reliable and does not significantly interfere with analog signaling.

7.1.1 Digital Signaling Spectrum

The digital signaling spectrum is defined as the frequencies from 500 Hz to 10 kHz (with -40dB per decade below 500 Hz and -20 dB per decade above 10 kHz). This is represented in Figure 12 below:

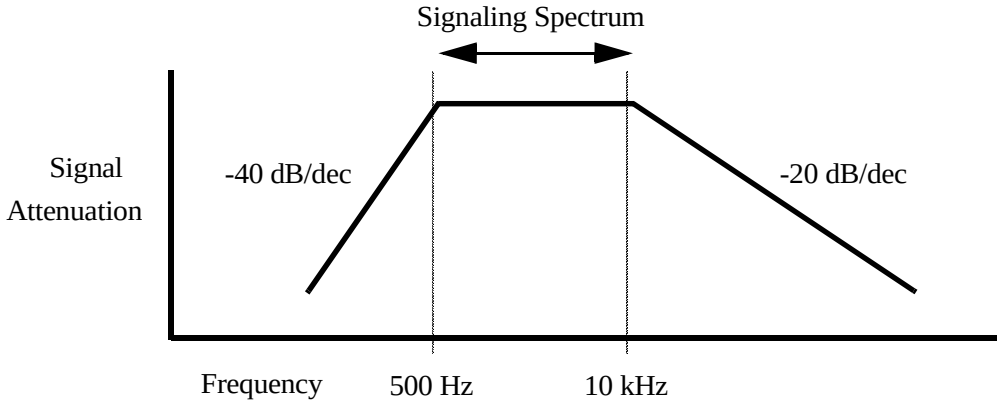


Figure 12. Digital Signaling Spectrum

All digital signaling devices are required to limit the amount of energy emitted during carrier start/stop within the analog signaling spectrum (Section 7.3.2.1). In addition, spurious energy outside the digital signaling spectrum may interfere with analog signaling, create crosstalk or produce other undesirable effects. Even though devices are not required nor tested for spurious energy outside the digital signaling spectrum, they should be checked in order to avoid the above mentioned effects.

7.1.2 Digital Signaling Characteristics

The HART protocol uses 1200 bps binary phase-continuous Frequency-Shift-Keying (FSK) to superimpose digital communications on to a 4-20 mA current loop. Devices signal with either current or voltage; all signaling appears as voltage when sensed across a low impedance. Phase-continuous fre-

quency-shift-keying requires the phase angle of the mark (1200 Hz = binary 1) and the space (2200 Hz = binary 0) to remain continuous at the 1200 Hz bit boundaries as shown below in Figure 13.

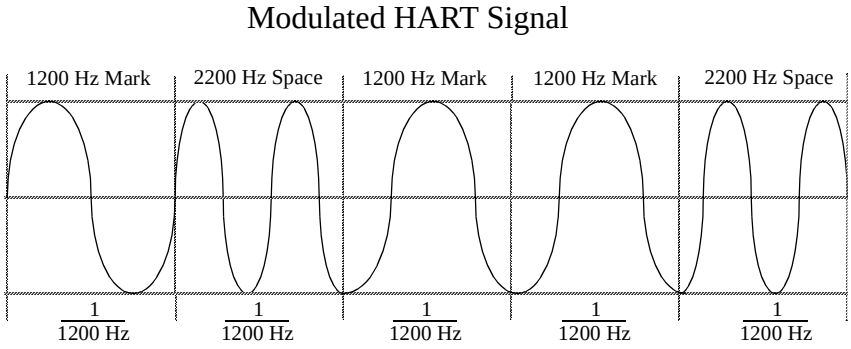


Figure 13. Example of Phase-Continuous Frequency-Shift-Keying

Other signaling requirements are contained in Table 2.

Table 2. Signal Timing

Parameters	Limits
Bit Rate (bps)	1200 ± 1%
Mark (logic 1) frequency	1200 Hz ± 1%
Space (logic 0) frequency	2200 Hz ± 1%
Carrier Start Time	5 bit times max.
Carrier Stop Time	5 bit times max.
Carrier Decay Time	15 bit times max.
Time from Carrier ON to Carrier Detect Assertion	6 bit times max. (note 1)
Time from Carrier OFF to Carrier Detect Disassertion	6 bit times max. (note 1)

Note 1: Devices produced prior to release of Revision 8.0 Physical Layer Specification may have up to 30 bit times.

7.1.3 Transmitted Waveform

The transmitted waveform is defined in Figure 14 as shown across the required test load. With the signaling element adjusted to emit either 1200 Hz or 2200 Hz tones, the signal must remain within the region indicated. This effectively specifies the signal amplitude, rise-time, overshoot, and droop (see Table 3). The waveform must be DC balanced as shown below in Figure 14.

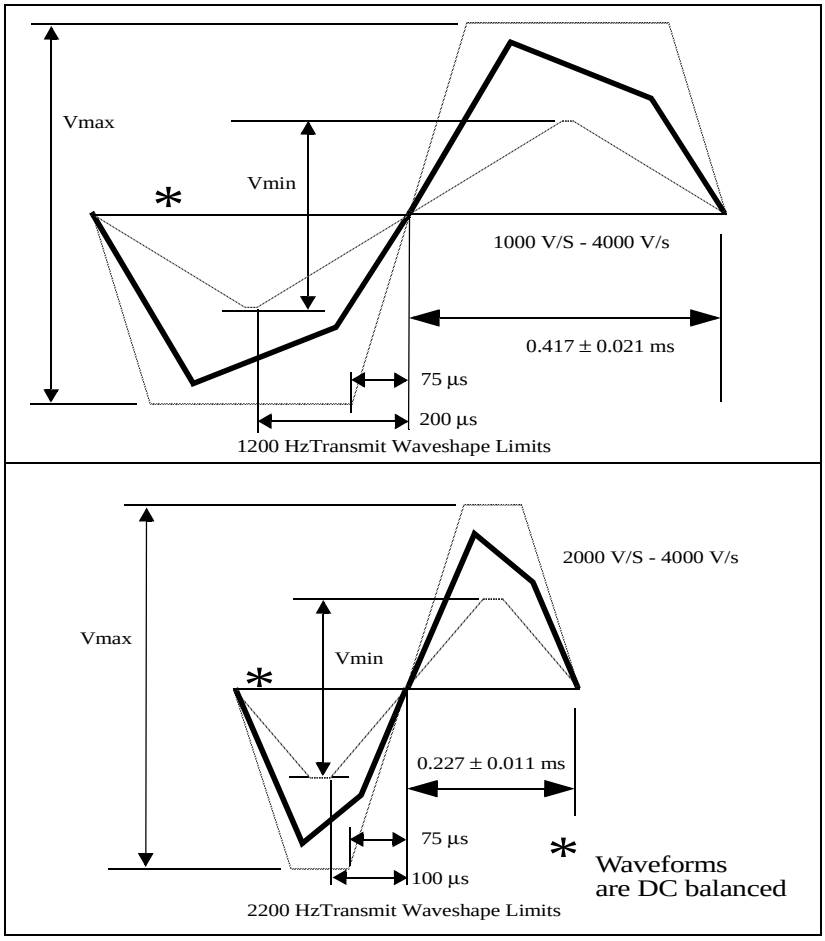


Figure 14. Transmit Waveform Limits

Table 3. Transmit Amplitude Limits

Impedance Characteristics	Vmin./; Minimum Amplitude	Vmax.; 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.

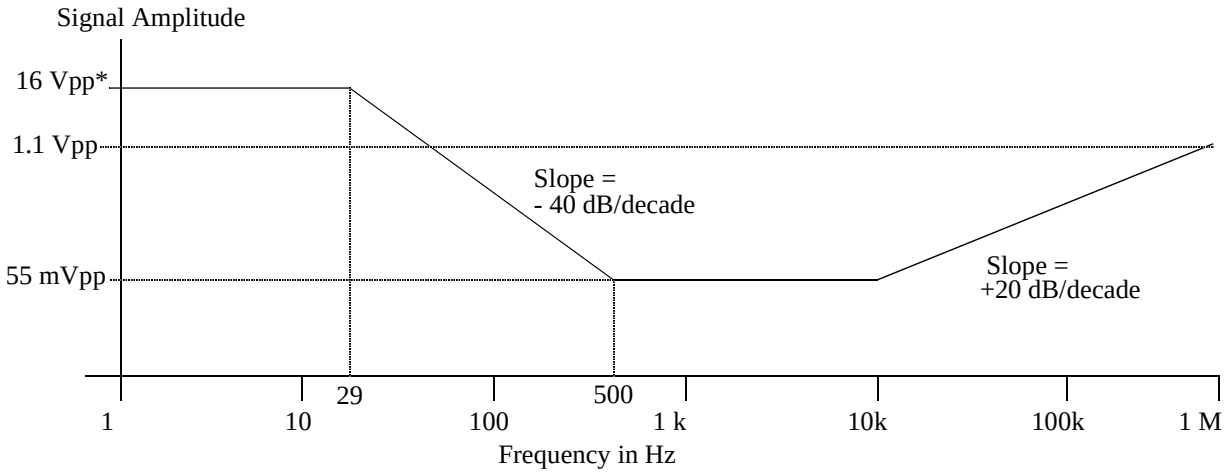
7.1.4 Receiver Characteristics

The receiver characteristics are common for all devices and given in Table 4 below.

Table 4. Common Receiver Requirements

Parameter	Conditions	Limits
Amplitude of HART signal 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 mV p-p, 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 Figure 15 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

The common mode requirements listed in Table 4 apply only to those devices that have all inputs floating with respect to ground.



* The maximum signal amplitude for low impedance devices with a fixed impedance will be the impedance value x 16 mA. For a system with a 250 Ω impedance, the maximum signal amplitude will be 4.0 V.

Figure 15. Receiver Out-of-Band Interference Limit (Peak-to-Peak Volts)

7.2 Analog Signaling Requirements

While no attempt is made within this specification to define analog signaling, a clear distinction is made between the analog signaling spectrum and the digital signaling spectrum in order to ensure signaling in one domain does not interfere with signaling in the other.

7.2.1 Analog Signaling Spectrum

The analog signaling spectrum is defined as the frequencies from DC to 25 Hz (with -40 dB per decade above 25 Hz). This is graphically represented by Figure 16 below:

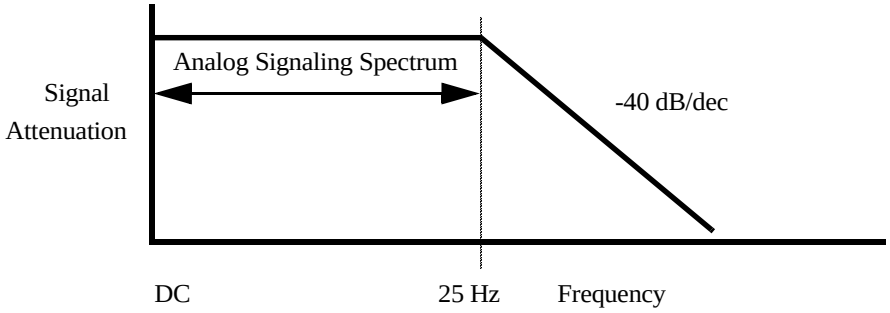


Figure 16. Analog Signaling Spectrum

Devices which generate analog signaling are required to limit the effects of this signal within the digital signaling spectrum.

7.2.2 Analog Signaling Interference on Digital Signaling

The analog output signal generated by an analog signaling device (i.e., transmitter or current output device) must not interfere with the communications signal. A device is considered to meet this requirement if its worst-case current signaling waveform does not produce any instantaneous peak voltages above 15 mV at the output of the filter[1] when applied to the specified test load and filtered through the digital test filter defined in Section 7.4.3.

In addition, 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 130 mVpp amplitude.

7.2.3 Analog Input Recommendations

It is important for analog input devices, such as current inputs and actuators, to filter the analog signal with a low-pass filter within the analog signaling spectrum defined above, to avoid interference from digital signaling.

7.3 Other Characteristics

7.3.1 Device Impedance

7.3.1.1 High Impedance Devices

Characteristics recommended for high impedance devices (with the exception of the secondary device given in section 7.4.1.1) over the normal frequency band are given in Table 5 below.

Table 5. 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.)

The recommended parameter limits are normally not included in this normative section, but are included here so that device designers can optimize their designs for longer cable lengths. To aid loop commissioning and multi-drop loop reliability, polarized devices are strenuously recommended to correspond to these values when reverse-connected. Independently-powered devices should also have these limits when not powered.

1. The 15 mV assumes a filter with unity gain.

7.3.1.2 Low Impedance Devices

The impedance of low impedance devices over the normal frequency band must remain within the limits given in Table 6 below.

Table 6. Low Impedance Device Electrical Characteristics

Parameters	Condition	Limits (notes 1, 2, and 3)
Impedance Magnitude, terminal-to-terminal	Receive only	230 Ω to 600 Ω
Impedance Magnitude, terminal-to-terminal	Sending only	Sending impedance may not exceed the receive-only impedance.

Note 1: There is no 1 kΩ test load for sending and receiving impedance specifications.

Note 2: Sending impedance and receiving impedances DO INCLUDE THE DEVICE'S CURRENT SENSE IMPEDANCE (typically a 250 Ω resistor).

Note 3: Impedance must not vary by more than ± 3 dB over the extended frequency band (500Hz to 10 kHz).

7.3.1.3 Secondary Device Impedance

Secondary device requirements given in Table 7 below apply over the normal frequency band.

Table 7. Secondary Device Electrical Characteristics

Parameter	Condition	Limits
Impedance Magnitude, terminal-to-terminal	Receive only	5 kΩ min.
Real part of impedance, terminal-to-terminal	Sending	(note 1)
Imaginary part of impedance, terminal-to-terminal	Sending	(note 1) (note 2)
Capacitance, terminal-to-ground	Sending or Receive	250 pF max.
Resistance, terminal-to-ground	Sending or Receive	100 kΩmin.

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

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

The requirements noted in Table 7 also apply for polarized units with the unit connected backwards, with or without power applied.

7.3.2 Interference to Analog Signaling

7.3.2.1 Carrier Start/Stop

To prevent interference to analog signaling, the carrier start/stop transients are recommended to decay fast enough that when the signaling waveform, using a 250 Ω test load, is passed through a 2-pole 25 Hz low-pass Butterworth filter (refer to the analog test filter defined in Section 7.4.2) the output of the filter does not exceed 10 mV at any time[1]. This does not apply to the application or removal of a network connection (i.e., temporarily connecting a secondary master to a network).

7.3.2.2 Occasional Secondary Connection Transients

A disruption to analog signaling may occur upon connection/disconnection of a secondary device to a network. Any resultant disruption must not exceed a peak effect of 1% of span (160 uA), averaged over a 10 ms period.

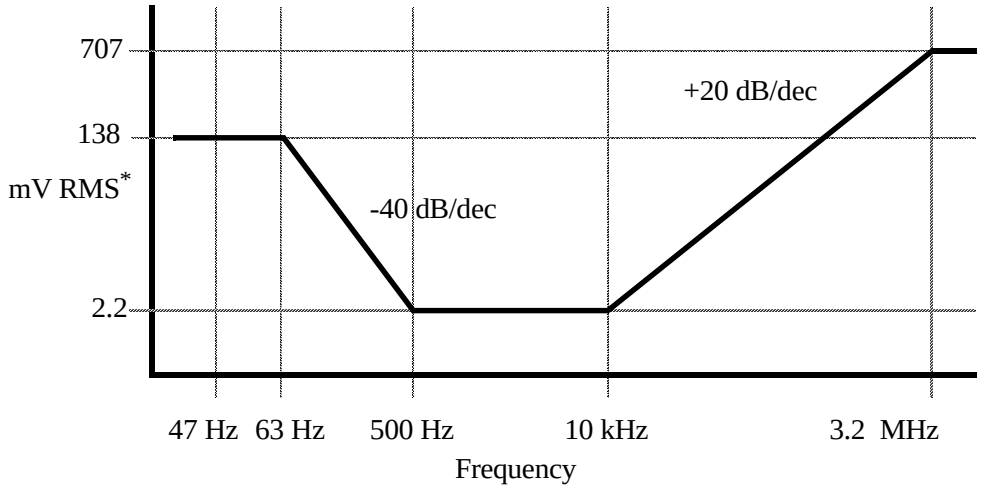
7.3.2.3 Cyclic Connection Transients

A disruption may occur when a secondary device or a low impedance device is cyclically connected/disconnected to a HART network. This type of cyclic connection is common when communications are multiplexed onto the network. Any transient that results from the cyclic connection must meet the analog signaling interference requirements outlined in Section 7.2.2 and the transient levels outlined in Section 7.3.2.1.

7.3.3 Output During Silence (Interference on Digital Signaling)

During silence the element output voltage, averaged over 1 second or more, must contain not more than 2.2 millivolt RMS of combined broadband and correlated noise in the extended frequency band as shown below in Figure 17. For devices capable of analog signaling, the requirement shall apply with it adjusted to produce a constant analog output current.

1. This requirement is tighter than all previous HART Physical Layer specifications. While it is highly recommended that all new designs meet the stated requirement, compliance with only the old requirement is acceptable. See Caution in Appendix A. The previous requirement was: The average voltage, averaged over a period of 10 ms, following application or removal of the carrier, must be less than 50 mV. During this time the transient must decay to less than half of its starting value.



Note: For sinusoidal noise Vpp = 2.8 x VRMS
For white noise Vpp ≅ 6 x VRMS

Figure 17. Allowable Output Noise

7.4 Test Requirements

7.4.1 Test Loads

Test loads are required when testing a device for conformance to the HART Physical Layer Specification. Unless otherwise indicated, the presence of this test load is assumed and all specified parameters are measured across the test load. The appropriate physical connection of the test load will vary with device type. In most cases, the test load is purely resistive and part of the DC current path. In the case of analog signaling devices such as transmitters and current output devices, the test load may also serve as the current sense impedance.

In some cases, it may be necessary to prevent DC current flow through the test load. When this is necessary, a 100 microfarad DC blocking capacitor may be placed in series with test load and the specified parameters may then be measured across the series combination of the capacitor and test load resistor. For example, this would be required for a voltage input or voltage output device where a purely resistive test load would cause abnormal DC current flow.

The test load value for all device types are shown below in Table 8.

Table 8. Device Test Loads

Device Type	Device Impedance	Test Load Resistance
Current Input	Low	1000 Ω ± 1%
Current Output	High	500 Ω ± 1%
Voltage Input	High	500 Ω ± 1%
Voltage Output	Low	1000 Ω ± 1%
Secondary	High	500 Ω ± 1%
Transmitter	High	500 Ω ± 1%
Actuator	Low	1000 Ω ± 1%
Non-DC Isolated Bus Device	High Low	500 Ω ± 1% 1000 Ω ± 1%
DC Isolated Bus Device	High Low	500 Ω ± 1% 1000 Ω ± 1%

Example test load topologies are shown below in Figure 18.

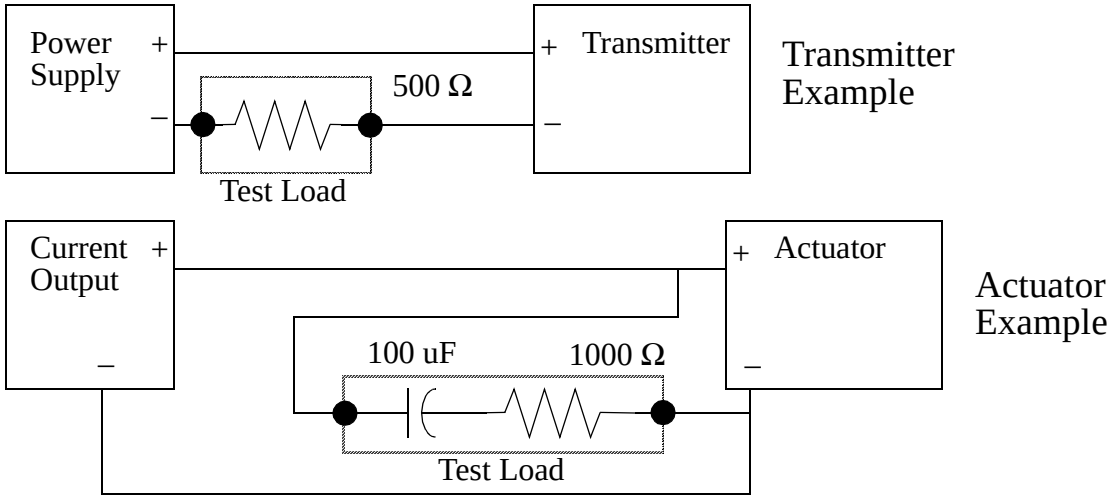


Figure 18. Example Test Load Topologies

7.4.2 Analog Test Filter

The purpose of the analog test filter HCF_TOOL-32, is to define the amount of energy a digital signaling device may generate from assertion or removal of its carrier (see Section 7.3.2.1) in the analog signaling spectrum. The low-pass analog test filter is specified to have a response within the analog signaling spectrum specified in Section 7.2.1.

7.4.3 Digital Test Filter

The purpose of the digital test filter HCF_TOOL-31, is to define the amount of energy an analog signaling device may generate in the digital signaling spectrum. The digital test filter is specified to have a flat response within the digital signaling spectrum specified in Section 7.1.1.

7.5 Cable Characteristics and Lengths

7.5.1 Cable Types

Cable must be one or more single-twisted pair shielded or multiple-twisted pair with overall shield. Single and multiple-pair may be combined in a given network provided all the devices at one end (typically the DCS end) of the multi-pair cable share a common shield or chassis ground, and the overall shield is connected to this ground. Unshielded cable may be used if it is demonstrated that ambient noise or crosstalk does not effect communication.

7.5.2 Recommended Minimum Conductor Size (Diameter)

Below 5000 ft. total length: #24 AWG (0.51 millimeter diameter).

Above 5000 ft. (single pair) total length: #20 AWG (0.81 millimeter diameter).

7.5.3 Calculated Single-Pair Length

The maximum length of cable per HART network is dependent on the characteristics of the devices connected to the network and the characteristics of the cable to be used.

To determine the maximum length of HART networks, Figure 19 through Figure 23 graphically estimate cable length based on the device and cable parameters as defined below. Figure 19 gives a direct unit length for the most common HART network, a single device used in conjunction with a 250 Ω current sense resistor, and without a miscellaneous series impedance. Figure 20 through Figure 23 indicate the total allowable cable capacitance, from which a cable length can be calculated, for HART networks that contain multiple devices and no Miscellaneous Series Impedance. For HART networks

that contain a Miscellaneous Series Impedance, additional graphs similar to those shown in Figures 20-23 are contained in Annex B. For all cable length estimates, the following parameters are required:

1. *Parallel Device Capacitance*: The summation of the C_X values of all connected devices. Refer to the Physical Layer Test Specification (HCF_TEST-2) for the method of determining the C_X value of a device.

2. *Parallel Device Resistance*: The parallel combination of the R_X values of all connected devices. Refer to the Physical Layer Test Specification for the method of determining the R_X value of a device. Typically there is only one low impedance device in the network (e.g., the DCS current sense resistor in a Transmitter loop) and it dominates this value. If all high-impedance devices on the network have input resistance ≥100 kΩ (the recommended minimum), their effect on the parallel device resistance will be negligible and the R_X of the single low-impedance device may be used for the Parallel Device Resistance value.

3. *Miscellaneous Series Impedance*: The miscellaneous series impedance value for a network is the sum of the maximum impedance (between 500 Hz and 10 kHz) of all devices connected in series between two communicating devices. A typical non-intrinsically safe loop will have no miscellaneous series impedance. Passive IS barriers and current indicators are examples of such devices. Note: Series topologies, such as field devices with PID capability or split-ranged Actuator devices, are analyzed by treating one of the field devices as a miscellaneous series resistance while analyzing the network for the other.

4. *Cable capacitance per unit length*: (feet or meters) The capacitance from one conductor to all other conductors (including the shield if shielded). This value is usually available from cable manufacturer.

5. *Cable resistance per unit length*: (feet or meters). This value should be available from the cable manufacturer. Table 14 in Annex B contains the resistance values of some common copper wire sizes. The resistance per unit length is for a single wire but the length calculations and charts take into account the resistance of both wires.

In a HART network, long cable lengths are possible when the dominant low impedance device is approximately 250 Ω, low capacitance good-quality cable is used, and each high impedance device has a low input capacitance (less than 5000 pF) and a high input resistance (greater than 100 kΩ).

7.5.3.1 Example Cable Length Calculations

Example 1. Single Device, Parallel Network Resistance = 250 Ω

Device Capacitance: 5000 pF

Cable Capacitance: 55 pF/ft.

Cable Resistance: 0.015 Ω/ft. (22 AWG)

From Figure 19, using cable capacitance (C_X) of 55 pF/unit length and resistance (R_X) of 0.015 Ω/unit length, a direct reading of the corresponding length on the y-axis is approximately 3300 feet (unit length of feet from above parameters).

Example 2. Multiple Device Network

Given parameters:

Device Capacitance: C_{DEVX} = 5,000 pF, C_{DEVY} = 10,000, C_{DEVZ} 10,000 pF

Device Resistance: $R_{DEVX} = R_{DEVY} = R_{DEVZ}$ =100 kΩ

Total Device Capacitance = 5,000 + 10,000 + 10,000 = 25,000 pF

Low Impedance Device Resistance = 250 Ω

Cable Capacitance: 400 pF/m

Cable Resistance: 0.0368 Ω/m (0.800 mm)

Calculated parameters:

Cable Capacitance/Resistance = 400 / 0.0368 = 10,869

Combined Parallel Resistance = 250 Ω (use Low Impedance Device value since high impedance devices are ≥ 100 kΩ).

The cable capacitance/resistance ratio is rounded to the nearest value of 1000, 2000, 5000, or 10000, corresponding to the graphs in Figure 20 through Figure 23. For the above example, the ratio is closest to 10000, which correlates to Figure 23.

From Figure 23, using an Rp of 250 Ω and Total device Capacitance of 25,000 pF, the allowable cable capacitance derived from the y-axis is 200,000 pF.

The maximum allowable cable length is calculated by dividing the allowable cable capacitance by the capacitance (per unit length) of the cable listed above. In this example, the maximum allowable cable length is (200,000 pF) / (400pF/m) = 500 m.

Example 3. Multiple device network with 100 Ω Miscellaneous Series Impedance

All parameters are the same as Example 2 except a series impedance of 100 Ω is assumed.

Instead of using Figure 23, you would use Figure 51 in Annex B. An R_p of 250 Ω and total device capacitance of 25000 pF yield the allowable cable capacitance derived from the y-axis is 145,000 pF.

The maximum allowable cable length is calculated by dividing the allowable cable capacitance by the capacitance (per unit length) of the cable listed above. In this example, the maximum allowable cable length is (145,000 pF) / (400pF/m) = 363 m.

7.5.3.2 Interpolation of Graphs

When the system parameters are between values shown in the charts, it is up to the user to interpolate between the values shown.

7.5.4 Maximum Multi-Pair Length

If multi-pair cable is used with single-pair cable to form a network, the total length of cable in this network is determined as the LEAST of the following values:

1. 5000 ft. (1500 meter)
2. The length as determined by following Section 7.5.3.
3. The length as determined by following Section 7.5.3 with the parallel network resistance is the largest value of any HART network in the multi-pair cable.

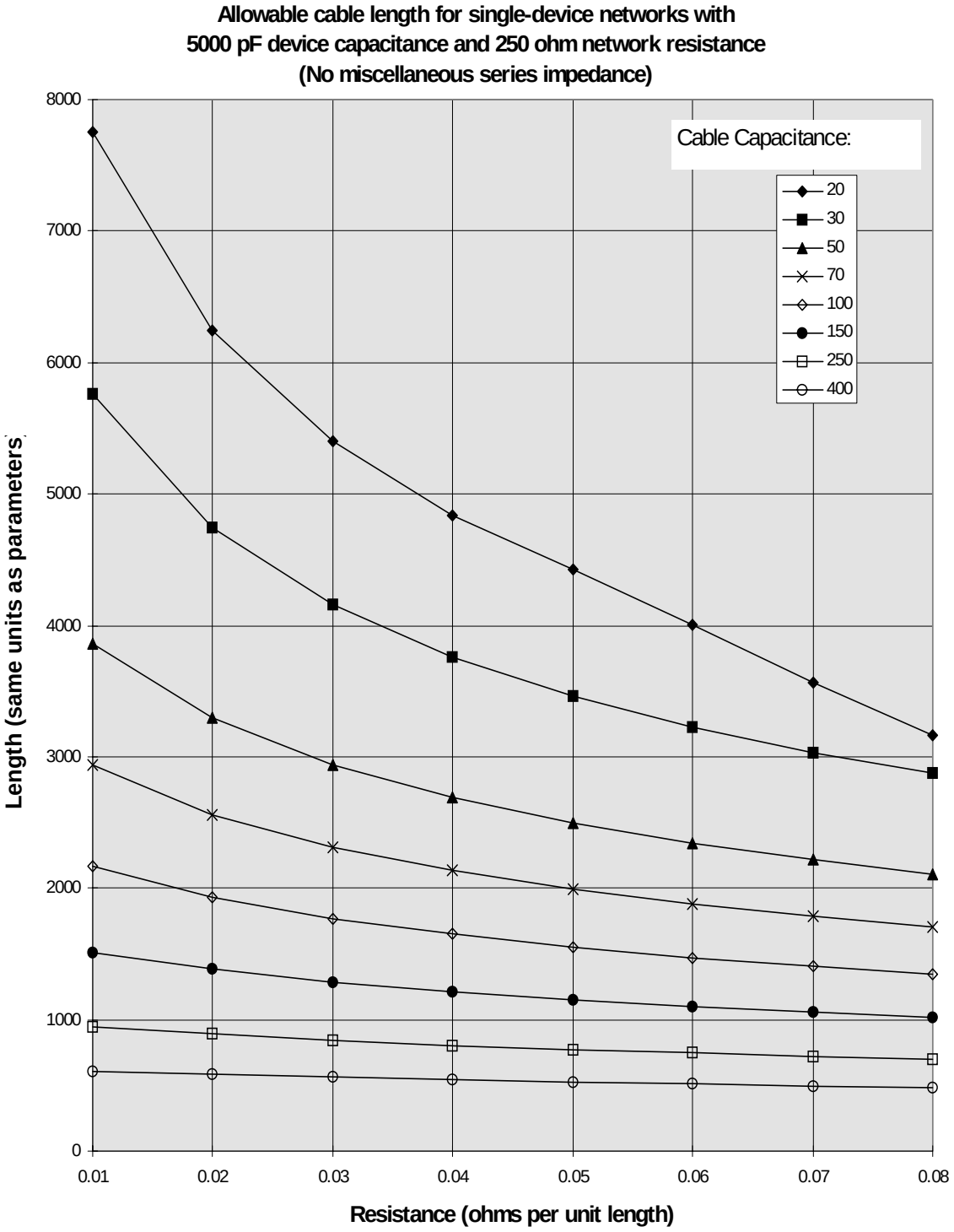


Figure 19. Length Graph - Single Device Network

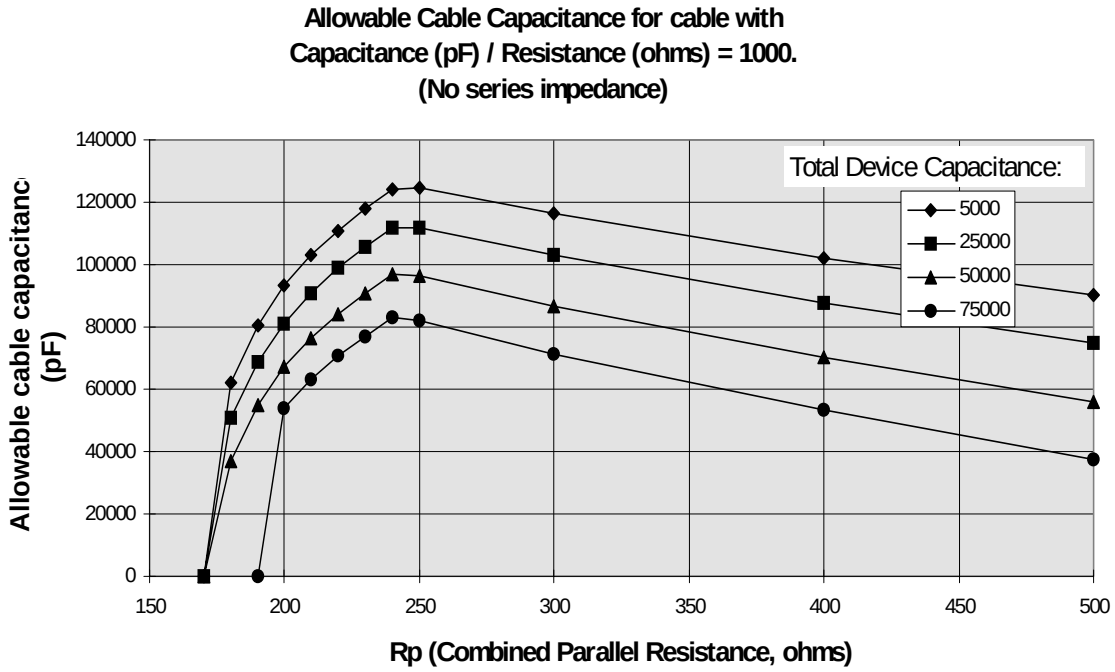


Figure 20. Length Graph, Capacitance/Resistance Ratio = 1000

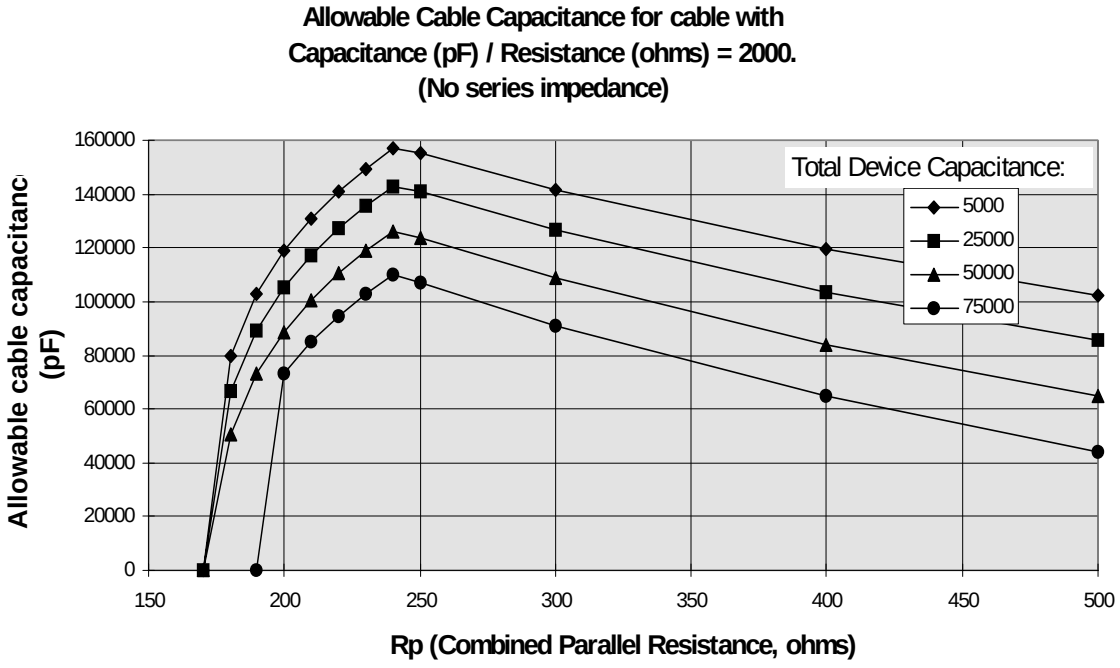


Figure 21. Length Graph, Capacitance/Resistance Ratio = 2000

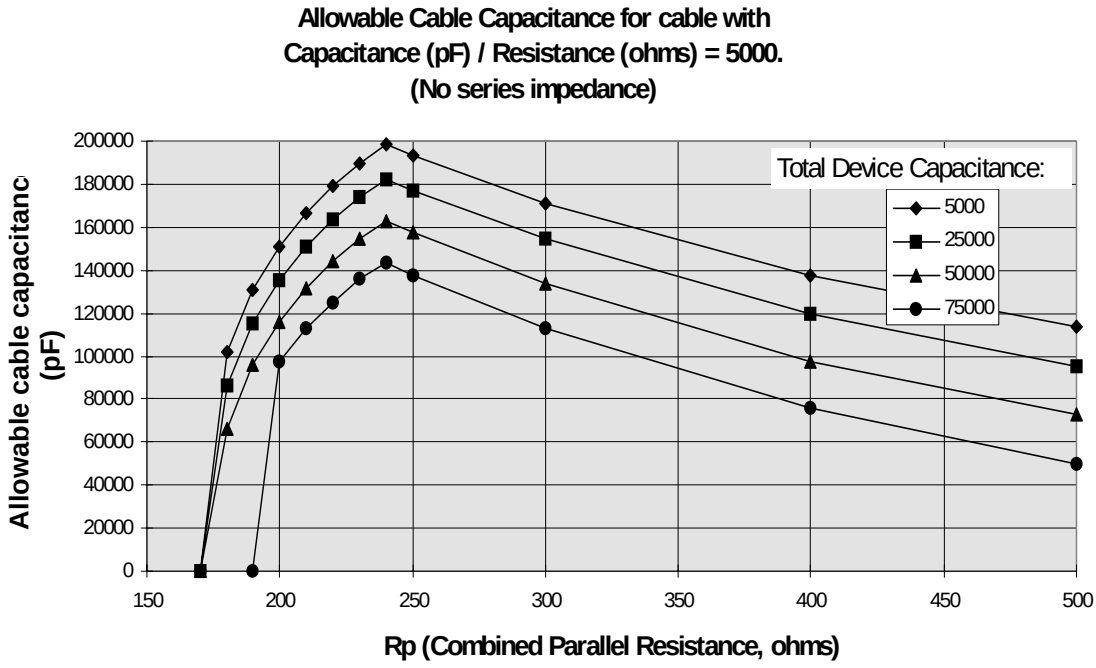


Figure 22. Length Graph, Capacitance/Resistance Ratio = 5000

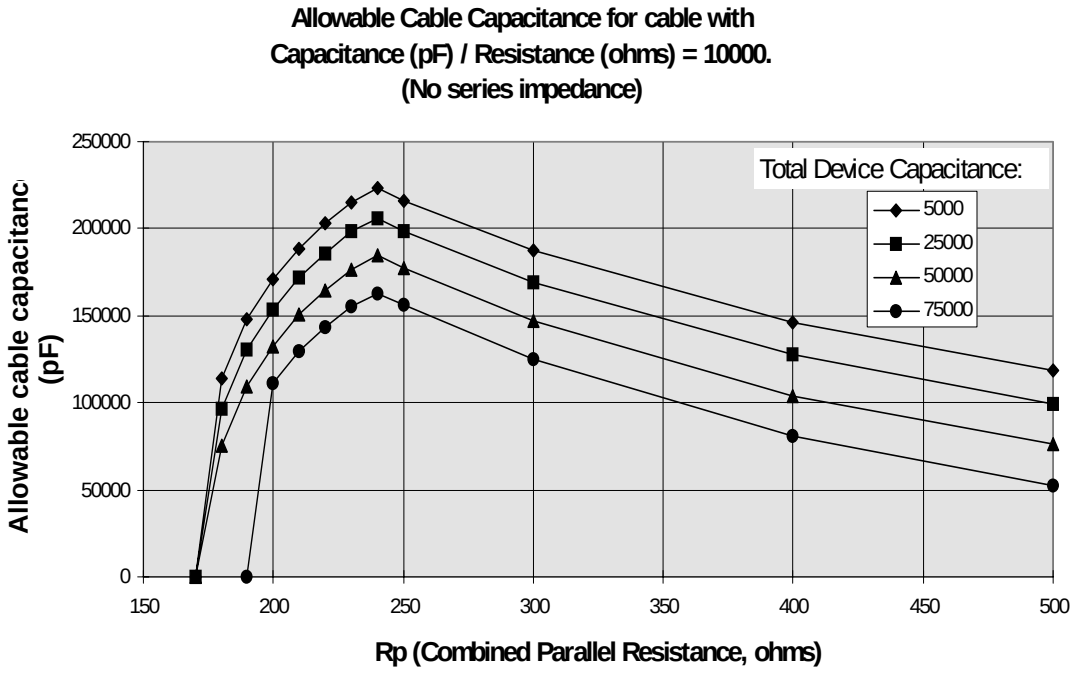


Figure 23. Length Graph, Capacitance/Resistance Ratio = 10000

8 NON-COMMUNICATING NETWORK DEVICES

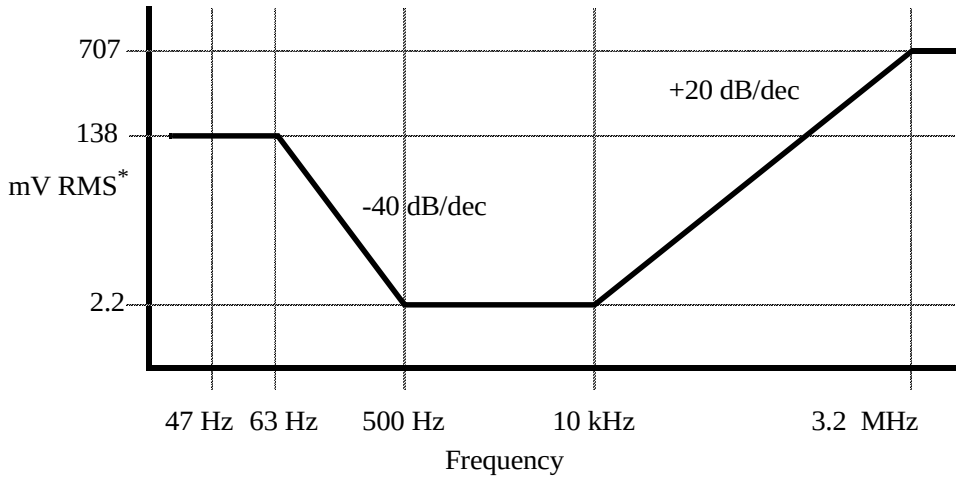
8.1 Network Power Supply

The network power supply provides DC power to the network. Any fuses, current limit resistances or supply resistances that are normally part of or used with the network power supply are assumed to be contained in the power supply. The network power supply requirements are stated in Table 9 and shown as a function of frequency in Figure 24 below.

Table 9. Network Power Supply Characteristics

Parameter	Condition	Limits
Ripple	All rated loads, 47 Hz to 63 Hz All rated loads, 94 Hz to 126 Hz	138 mV RMS 35 mV RMS
Noise	All rated loads, Extended Frequency Band	2.2 mV RMS max. (note 1)
Noise	All rated loads, Outside Extended Frequency Band	Within limits shown below in Figure 24
Impedance Magnitude	All rated loads, Extended Frequency Band	10 Ω max.

Note 1: It is permitted to combine the allowed noise of the Master with the allowed noise of the network power supply, that together they do not exceed the RSS (Root Sum Square) value of 3.1 mV RMS.



Note: For sinusoidal noise Vpp = 2.8 x VRMS
For white noise Vpp ≅ 6 x VRMS

Figure 24. Power Supply Ripple

In intrinsically safe applications, the network power supply voltage and barrier shall be chosen and operated such that an AC voltage of up to 1.4 volt p-p may be superimposed onto the DC at the hazardous (network) side of the barrier.

8.1.1 Power Distribution and Barriers

The network power supply is generally located at the current input device and can be connected as illustrated in Figure 25 below

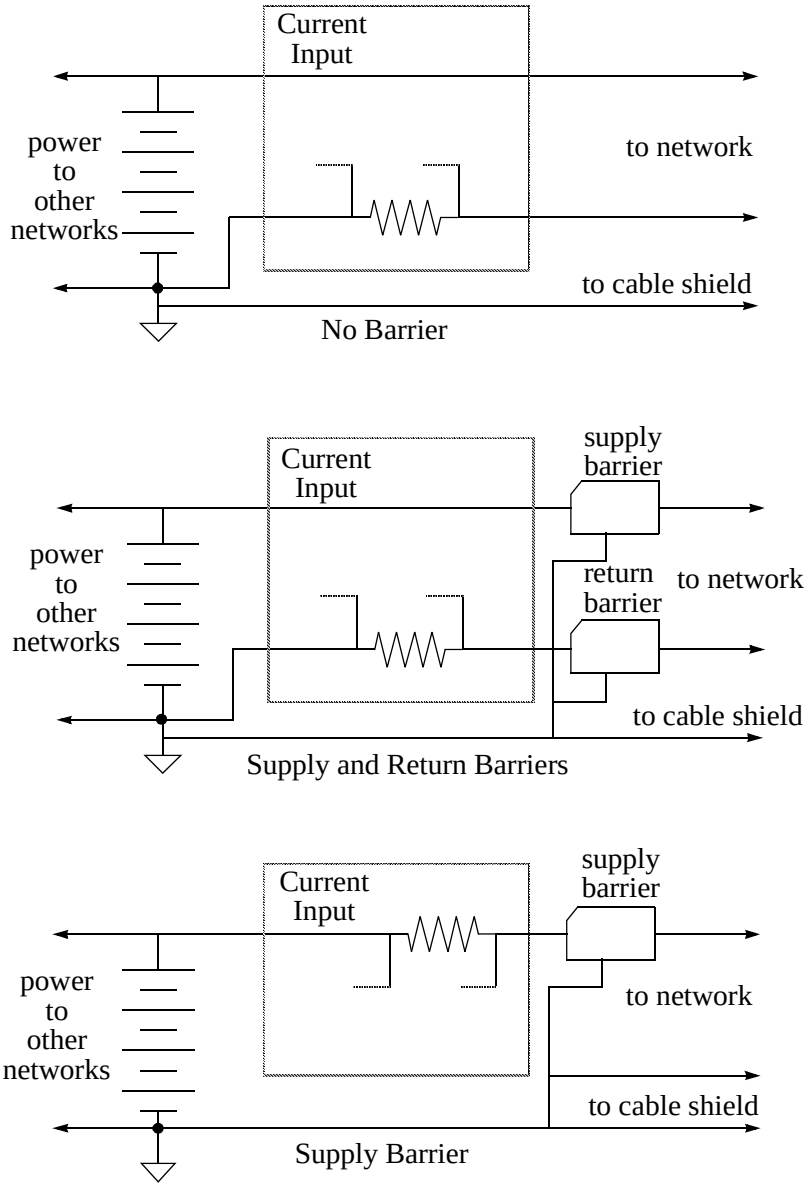


Figure 25. Network Power Supply Connections

When a network power supply is not used, the power supply in any of the configurations of Figure 25 is removed and replaced with an impedance not exceeding the permitted power supply impedance of Section 8.1. A single network power supply may power more than one network, provided that it is connected to multiple networks as shown in Figure 25.

Device types which require power from sources other than the network may be powered by twisted pairs in the same multi-pair cable that carries signal pairs, provided that variations in current consumption of these devices is within the limits imposed in Section 7.2.2.

8.1.2 Shielding and Grounding

Figure 26 shows the preferred grounding schemes. The cable shield must be grounded at one point only. This is usually done in the control room at or near the source of loop power. However, the ground connection may alternatively occur in a junction box or other suitable location in the field area. Care must be taken to avoid an inadvertent connection of grounded metal objects to the shield.

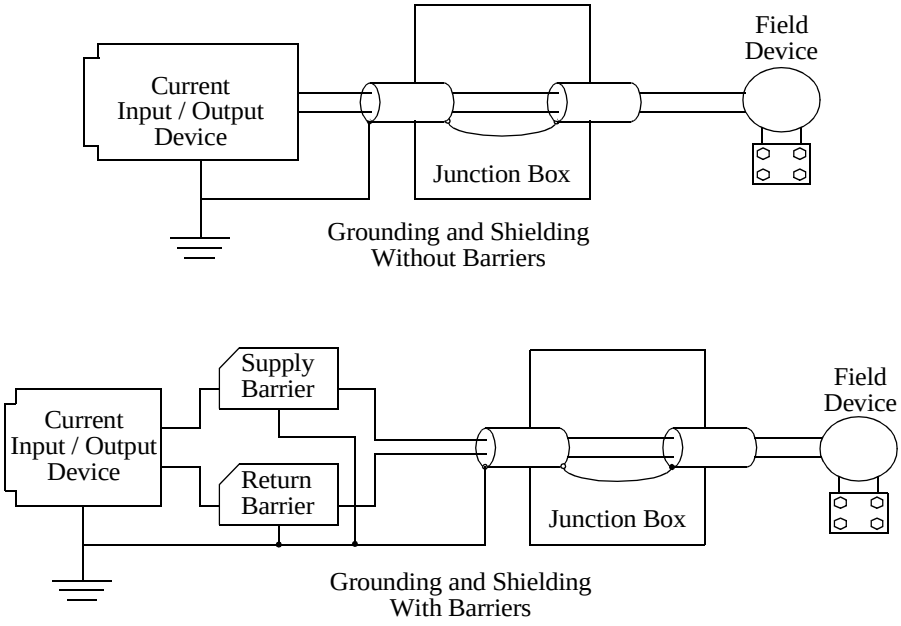


Figure 26. Grounding and Shielding

Multiple networks that share a common connection should be grounded at the respective primary master or analog controller.

A cable shield is usually left open (unconnected) at a field device. Alternatively, the shield may be connected to the field device housing or the internal shield surrounding the device's circuits under

either of the following conditions: (1) the device housing or the internal shield must be isolated from ground, or (2) the connection of shield to ground is the only point in the network at which the shield is grounded.

For junctions not located at a signaling element, the shields of all cables brought to the junction are usually connected. To surround otherwise exposed wiring, cable shields may be connected to junction boxes and wiring panels if the junction boxes or panels are isolated from ground or if the connection to ground is the only point at which the network shield is grounded.

Other grounding and shielding arrangements may be used if the coupling and RFI/EMI do not interfere with HART digital signaling.

8.2 Barriers

The requirements of barrier impedance facing the hazardous side(s) is given in Table 10. The safe side(s) are assumed to be connected to the silent primary master (or analog controller), and the master and barrier combination is assumed to be operating normally.

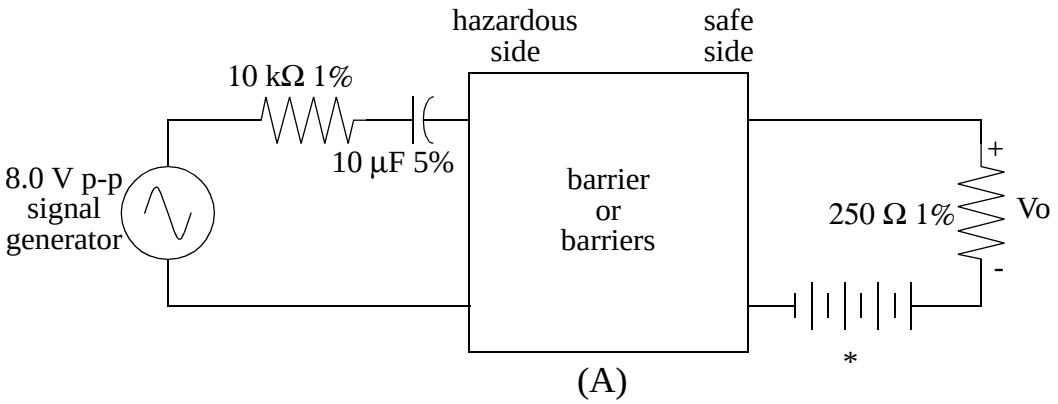
Table 10. Barrier Impedance Requirements

Parameter	Condition	Limits
Real Part of Impedance	Extended Frequency Band, Barrier and Master powered or biased for nominal operating conditions	230 Ω to 600 Ω
Imaginary Part of Impedance	Same as above	-350 Ω to +350 Ω

The attenuation and delay distortion of a barrier must within the limits defined in Table 11 below.

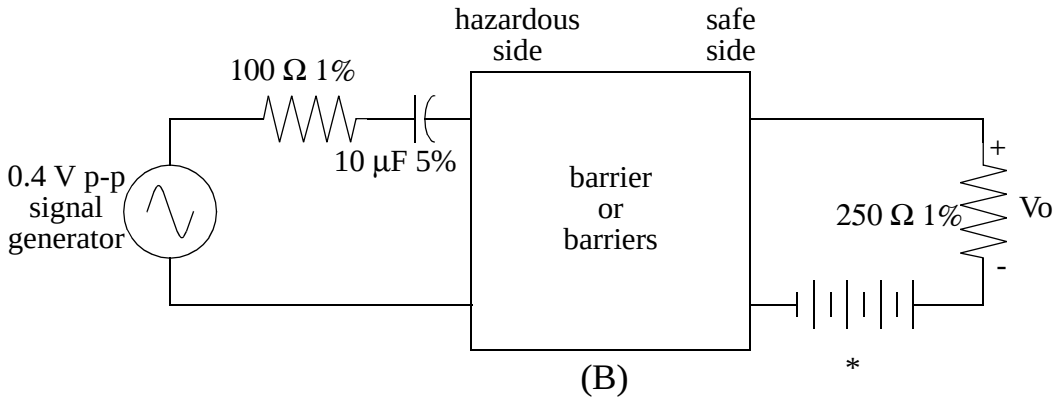
Table 11. Barrier Attenuation and Delay Requirements

Parameter	Conditions	Limits
Output Voltage Hazardous Side to Safe Side, first test	Frequency Band, Test circuit of Figure 27A	185 mVpp min. 800 mVpp max.
Output Voltage Hazardous Side to Safe Side, second test	Frequency Band, Test circuit of Figure 27B	135 mVpp min. 400 mVpp max.
Output Voltage Safe Side to Hazardous Side	Frequency Band, Test circuit of Figure 27C	270 mVpp min. 400 mVpp max.
Delay Distortion	Frequency Band, Each of above test circuits	50 µs max.



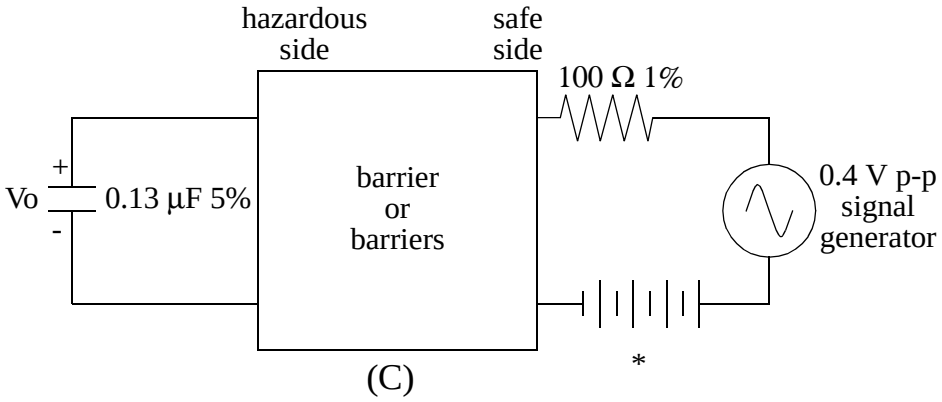
* Polarities should be established and bias sources or power supplies added according to the particular barrier being tested.

Figure 27A. Barrier Test Circuit



* Polarities should be established and bias sources or power supplies added according to the particular barrier being tested.

Figure 27B. Barrier Test Circuits



* Polarities should be established and bias sources or power supplies added according to the particular barrier being tested.

Figure 27C. Barrier Test Circuits

8.3 Miscellaneous Hardware

Miscellaneous hardware may be connected in series with a field device or in parallel with field devices according to function. Miscellaneous hardware may not be connected in series with a network power supply so that it becomes a common element to two or more networks which share the same power supply. Miscellaneous hardware may not be connected between the network and ground. A network may accommodate more than one component of miscellaneous hardware provided that the electrical characteristics of the combined devices are within the limits given in Table 13.

Table 12. Miscellaneous Hardware Characteristics

Parameter	Conditions	Limits
Capacitance to Ground	Extended Frequency Band	1000 pF max. recommended
Resistance to Ground	Extended Frequency Band	100 kΩ min.
Impedance If Series Connected	Extended Frequency Band	100 Ω max. recommended (note 1)
Series Impedance Rate of Change	Extended Frequency Band	± 5 Ω per ms max.
Impedance If Parallel Connected	Extended Frequency Band	10 kΩ min. recommended (note 2)
Parallel Impedance Rate of Change	Extended Frequency Band	± 5 kΩ per ms max.
Broadband or Correlated Noise or Interference	Extended Frequency Band, 500 Ω load	2.2 mV RMS max. averaged over 1 second or more

Note 1: The maximum impedance magnitude (in the extended frequency band) of series-connected miscellaneous hardware must be included as series resistance in the network length determination.

Note 2: The minimum impedance magnitude (in the extended frequency band) of parallel connected miscellaneous hardware must be included as parallel resistance in the network length determination.

The above recommended parameter limits are normally not included in the normative section, but are included here so that system designers can optimize their networks for longer cable lengths.

ANNEX A. DISCUSSION AND DERIVATION OF SPECIFICATIONS

In the following annex, an attempt is made to explain or to show how the parameters were derived in the body of the specification. Sections labelled A-x.x refers to corresponding sections of the specification. For example, A-5.3 corresponds to paragraph 5.3, “Device Connection Types” on page 22 and explains the characteristics of different device types.

A - 5.3 Device Connection Types

The device connection types are intended to differentiate between devices connections as necessary to be able to apply network configuration rules. The references to device types in Revision 7.2 of the Physical Layer Specification are intended to make it easier for those familiar with 7.2 to understand the new definitions.

The requirements for publishing certain parameters of device connections come from the need for this information to facilitate the network length calculation, and also to facilitate DC voltage/power analysis for HART loops.

Characteristics:

1. The worst-case unbalanced network must be considered when determining these parameters because most HART networks are unbalanced, and the lower impedance to ground could exist on either the high or low side of the network. If a device has a lower impedance to ground on one side than the other, and that device is connected to a network where the other side has a low impedance to ground, the device will exhibit a low terminal-terminal impedance as a result. To prevent this from causing application problems, the lowest value must be published as the device’s parameter.

   Since these devices are isolated from ground, R_{tg} and C_{tg} can be considered negligible.

2. Generally there will only be one device on a network that is not DC isolated from ground. The nature of the connection to ground must be understood to analyze networks from the imbalance standpoint as well as to determine the applicability of certain I.S barriers. In some cases, knowing the nature of ground connections may allow the connection of more than one grounded device to a network.

3,4. It is important that the manufacturers specify DC voltage and the current requirements at the levels where communication parameters are valid, and NOT merely the levels at which the instruments begin to operate. For example, a transmitter manufacturer should not just specify the voltage at which the transmitter starts to control the current, but rather a value that allows the current to be modulated in response to process changes and as a means of communication.

5. It is important for devices that signal with analog current to publish the limits of the

current output so the loop voltage analysis can be done at the extremes. It is clearly possible to construct a loop that will work at 20 mA, but will saturate and not work at 22 mA. The analysis of the loop must be done to insure that communications are still possible in power wind-up conditions.

6. It is not a requirement that a Low Impedance device have a pure resistive impedance. In some cases the impedance can be quite complex. For reasons stated in paragraph 6, it is requested that all manufactures will list their minimum and maximum impedance magnitude in the HART Extended Frequency Band.

A - 6.2 Combination of Elements

Multi-Dropped Networks are restricted to Digital Signaling (with the exception of 1 analog signaling device per Rule Number 2) to prevent interference between Field Instruments. However, irrespective of interference, a combination of Analog Signaling and Multi-dropped Digital Signaling is not a typical network configuration. The table shows that a Point-to-Point Network need not have either a Primary or Secondary Master. This situation would exist, for example, when only an Analog Controller is used, the single Field Instrument having been programmed by a Secondary Master that was subsequently disconnected.

The number of Field Instruments is restricted to no more than 15 to avoid excessive noise from otherwise silent Signaling Elements.

A - 6.2.1 Rule Number 1

Since the network length is maximized at about 250 Ω due to the time constant (capacitive roll-off restrictions), it will be advantageous for low impedance devices to be near that, and two such devices in parallel would create too low of a network impedance for adequate signal amplitude. However, to offer design flexibility, the section is written to allow multiple low-impedance devices as long as the parallel combination gets no lower than the specified minimum.

The minimum value of 170 Ω is derived from the length calculation. Having the combined parallel impedance of devices on a network being as low as 170 Ω will result in a usable cable length of 0 feet. It is recommended that the combined impedance should be near 250 Ω for networks requiring longer cable lengths.

A - 6.2.2 Rule Number 2

Since analog signaling is a form of interference to digital signaling, and since the low frequency rejection requirements of receivers were derived assuming the signal of one source, more than one source in parallel cannot be allowed without more restrictive filter requirements.

A - 6.2.3 Rule Number 3

This is the provision for multi-dropping. The restrictions are self explanatory.

A - 6.2.4 Rule Number 4

This is the provision for a handheld secondary master. Since the user is likely to only consider the permanently installed equipment when planning his networks, and since the precedent has been set for ignoring this device, and since multiple devices have already been designed to meet these requirements, it makes sense to uniquely specify it. It is possible to construct networks with 2 physical devices of this type, but at least one of the devices must be treated as an isolated bus device and included in the network calculations. The limit of one is driven solely by the fact that only one such device is assumed in the calculations.

A - 6.2.5 Rule Number 5

It is appropriate to remind the user that the cable length and combinations of devices are interrelated. The allowable length is determined by the impedance of the devices connected as well as by the cable properties.

A - 6.3 Example Topologies

The example topologies show the more common network configurations and are not intended to limit other new and unique applications.

When creating a Network, one must be careful not to violate any of the Network Configuration Rules outlined in Section 6.

Network topologies are possible that do not violate any of the Network Configuration Rules and yet may not allow HART communications between all devices on the Network.

A - 7.1.2 Digital Signaling Characteristics

A 1% tolerance on bit rate means that the last bit in each 11-bit character can be skewed by approximately 22% of one bit time between transmitting and receiving devices. Equipment designers are advised that some UARTs may not be compatible with this much skew.

Time from Carrier On/Off to Carrier Detect Assertion/Disassertion was decreased from the previous Physical Layer Revision 7.2 of 30 bit times to 6 bit times to rectify a timing issue in the Data Link Layer with Secondary Masters and Bursting Devices. With the commercially available HART modems today, the 6 bit time specification is easily met.

A - 7.1.3 Transmitted Waveform

The specification for transmitted waveform effectively provides:

1. A rise time requirement to limit coupling.
2. An upper limit on signal strength, also to limit coupling.
3. A lower limit on signal strength, to insure sufficient received signal.
4. A shape requirement to insure that the full signal power spectrum is being transmitted.

The waveform is measured ‘DC balanced’ such that the waveform is not simply placed in the specification envelope for the ‘best fit’. The oscilloscope measurement would be made by first referencing ground as the x axis and then recording the measurement with input AC coupled.

With revision 8.0, the transmit amplitude was increased to 800 mVpp to relax the waveform requirements for low impedance devices. Having a larger waveform envelope will enable low impedance devices that are capacitvely coupled to use lower value capacitors. Analysis did show a negligible impact on generated noise and crosstalk.

A - 7.1.4 Receiver Characteristics

The 120 mVpp minimum receive signal is derived as follows. The minimum Field Instrument signal current (Digital Signaling only) is 0.8 mApp. This applied to the worst case Network, having a 65 microsecond time constant, using as a minimum a Low Impedance Device of 230 Ω, yields a voltage magnitude of 130 mVpp (0.707 x 0.8 mApp x 230 Ω). A 10 mVpp margin subtracted from this leaves 120 mVpp.

The 1500 mVpp maximum receive signal is specified to ensure backwards compatibility and prevent signal clipping, for devices which may be installed into networks with higher impedances (sometimes due to long cable lengths) that may produce Digital Signaling of this magnitude.

The 1500 mVpp requirement is necessary to maintain backward compatibility with older HART networks that use a sense impedance of 1100 Ω.

The bit-error-rate requirement of Table 4 is included to insure that receiver circuitry does not degrade the communication beyond what should be possible, based on the theory of non-coherent demodulation of phase-continuous FSK. To achieve an error rate of 1 error in 10,000 requires a signal-to-noise ratio of 12 dB. With 1 dB of margin added to account for distortions in the receive circuits, this is 13 dB. With the added 1 dB, the error rate of 1 in 10,000 becomes very easy to meet. Therefore, the test is designed to be quite conservative.

If the input signal is 200 mV p-p, then the noise level is 15.88 mV RMS. Over the Extended Frequency Band, the required noise density is therefore 163 microvolt/root Hz. The Frequency Band, which contains the HART signals and extends from 950 Hz to 2500 Hz is considerably smaller than the Extended Frequency Band of 500 Hz to 10 kHz. The test noise level is purposely specified over the larger band so that an even better signal-to-noise ratio can be achieved using relatively simple filtering of part of the noise band. That is, a filter should include the 950 Hz to 2500 Hz band and exclude part of the 500 Hz to 10 kHz band.

Figure 15 represents the minimum interference that the receiver must tolerate.

The 16 volt maximum signal is derived as follows: The maximum combined cable resistance and Barrier impedance is limited to about 400 Ω , since it is impractical to use long cable lengths when Barriers are used. The 400 Ω combined with a maximum Network Impedance of 600 Ω, yields 1000 Ω. A worst case square wave from a Field Instrument will be 16 mApp. This, applied to the 1000 Ω, gives 16 Vpp.

The 55 mVpp (9.2 mV RMS noise x 6; where 6 is the approximate conversion from RMS noise to maximum combined p-p noise) asymptote corresponds to the expected maximum combined noise or interference in the Extended Frequency Band.

The receive filter can compromise receiver performance if it introduces too much delay distortion. The usual cure for this, without using delay equalizers, is to begin the filter roll-off far from the signal band edge. The filter is therefore a compromise between the need for small bandwidth to exclude noise and large bandwidth to prevent delay distortion. The delay distortion is usually only a concern at the lower side (950 Hz) of the band.

One of the primary functions of the receive filter is to reject the low frequency Analog Signaling and prevent it from compromising digital reception. In addition, high frequency components should also be attenuated to prevent interference above the Extended Frequency Band. To insure proper receiver operation, it is generally sufficient to attenuate out-of-band interference to a level of 0.1 (-20 dB) or less of the minimum receive signal. The minimum received signal is 130 mVpp. Therefore, the receive filter should attenuate out-of-band interference to less than 13 mVpp referred to the element network terminals. The out-of-band interference can be quite large as indicated in Figure 24. The recommended receive filter is a band-pass with the lower band edge being a 3-pole Butterworth with a 400 Hz cutoff frequency and the upper band edge being a single pole with a 2.5 kHz cutoff frequency as shown in Figure 28 below.

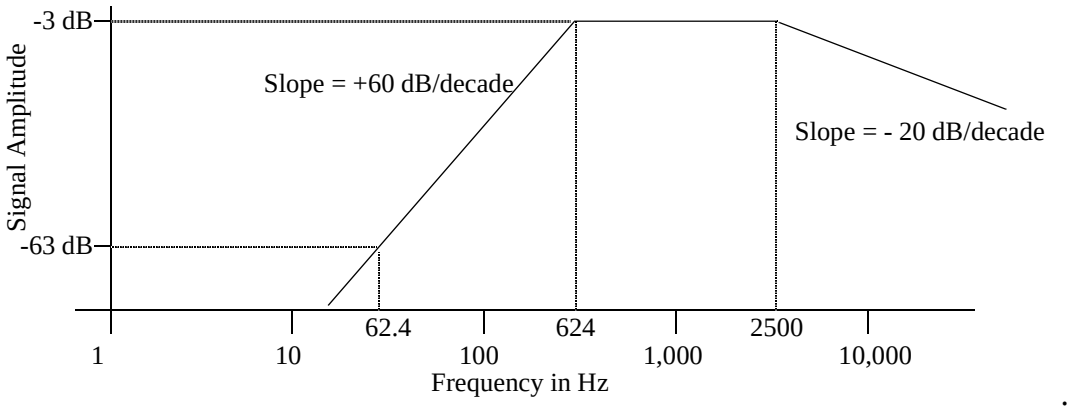


Figure 28. Receive Band-Pass Filter

A - 7.2.1 Analog Signaling Spectrum

Analog Signaling is limited to a 25 Hz bandwidth to prevent interference to the digital receiver. This bandwidth could be increased at the cost of raising the receive filter cutoff frequency. The 25 Hz cut-off frequency and the choice of receive filter given below represent a satisfactory compromise between the desire for fast Analog Signaling response and acceptable received digital signals. Simulations using a 16 mA p-p square wave (the worst possible process variable signal) have shown that the filter combination is satisfactory to prevent interference with Digital Signaling.

A - 7.2.2 Analog Signaling Interference on Digital Signaling

The derivation of the old limits was based on mathematical analysis showing that 9.2 mV RMS of noise from a single source was allowable. From that, a 26mV limit for a single interfering frequency was determined. Since a “single interfering frequency” implies a sinusoidal waveform, and current output waveforms are not usually sinusoidal, the limit was difficult to apply.

Given the fact that HART receivers typically have a bandpass filter similar to the HART filter specified for this test, and that they begin the demodulation process with simple hysteretic threshold detection of the zero crossings of the HART waveform, it appears that the peak voltage of the filtered waveform is a good measure of the ability of the interference to disrupt communications.

For these reasons, this specification presents the limit in easily interpreted and measured terms of peak voltage out of a known filter. To be consistent with the old claim that a 2-pole filter at 25 Hz was adequate, (known to have been tested successfully) the limit of this specification is set at 15 mVpeak, just above the level that would result from full-scale signaling through the 2-pole 25 Hz filter. Figure 29 illustrates this example.

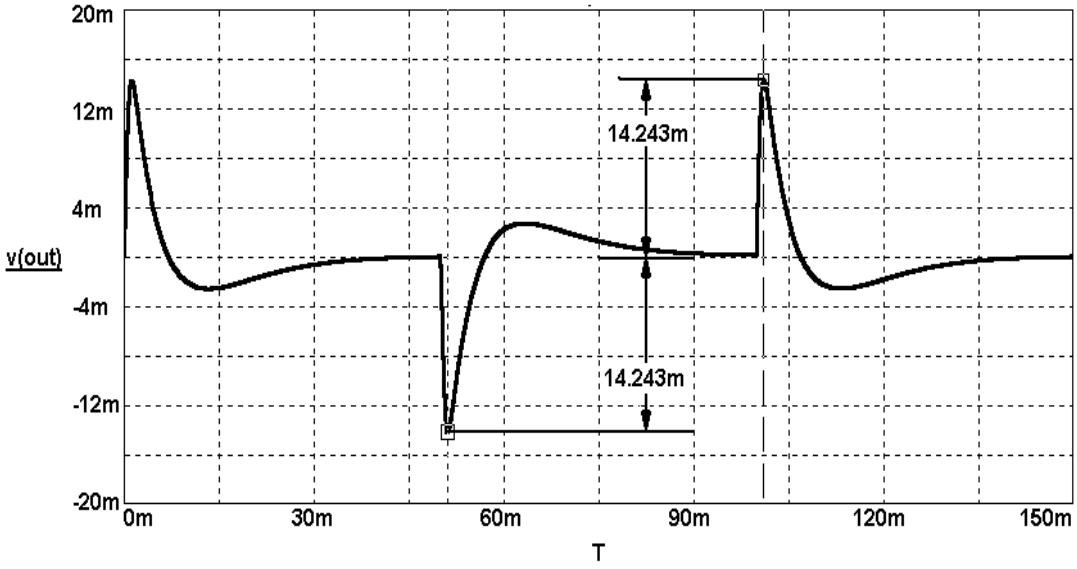


Figure 29. Output from HART filter with filtered 16 mA square wave input (500 Ω load)

For additional comparison, a 26 mVpp (52 uApp) 2.5 kHz sine wave would produce a HART filter output of 12.12 mVpeak.

The additional requirement that the device be capable of successful communication (bit error rate < 1 in 10,000) during worst-case analog signaling with the received HART signal attenuated to 130 mVpp amplitude, is stated to ensure that the design has allowed for worst-case signaling in its own sending and receiving circuits.

A - 7.3.1.1 High Impedance Devices

The recommended minimum values for these devices are intended to maximize the potential for long cables and multi-drop networks. It should not be difficult for the designer to meet these values in a traditional 2-wire transmitter design. These values were requirements in the Rev. 7.2 Physical Layer spec, but were relaxed to recommendations to allow innovative designs of High Impedance devices for which other design features may make the recommendations difficult or less important to meet.

The Terminal-to-Ground capacitance limitation is necessary to preserve isolation between a Field Instrument and ground, to prevent the formation of ground loops and other undesired signal paths. Since HART networks normally have a low impedance to ground at one point (usually a property of the control system connection or the power source for the network, and usually unbalanced) the pres-

ence of a low impedance to ground in any other device such as a field device would be just as much of a load to signalling as terminal to terminal loads.

Over the Extended Frequency Band, a High Impedance Device can be modeled as resistance, capacitance, and inductance combinations as shown below in Figure 30.

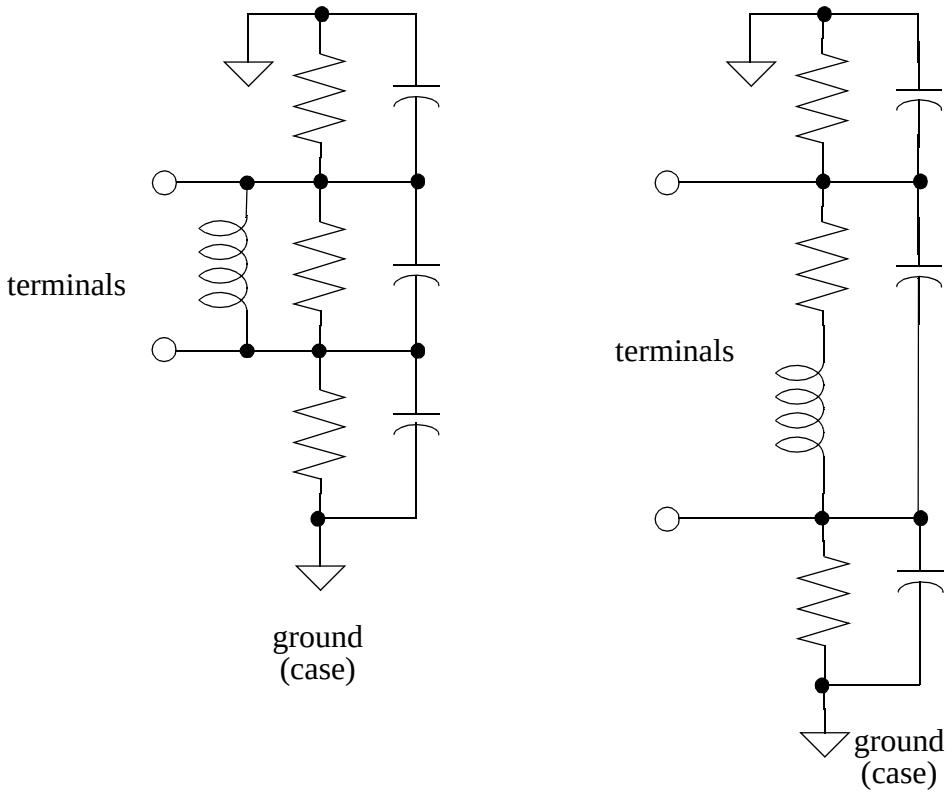


Figure 30. High Impedance Device Models

A - 7.3.1.2 Low Impedance Devices

The impedance requirements of section, along with the transmitted signal requirements of section 7.1.3, are intended to satisfy 6 conditions:

1. Provide a controlled, but relatively broad, range of resistance across which Analog Signaling and Digital Signaling voltages can be developed in response to the signaling currents from Field Instruments.

2. Provide adequate signal to the Network when transmitting.

3. Prevent excessive Network signals when transmitting, which could possibly lead to excessive master-to-master coupling.
4. Preserve quality (bandwidth) of both the transmitted and received signal.
5. Provide flexibility in signal coupling.
6. Provide all of the above with or without a Barrier.

Note: Impedance Magnitude is the resultant of the Real and the Imaginary Impedances.The previous Revision 7.2 specified both the Real and the Imaginary requirements on the transmit signal. Revision 8.0 simplified conformance testing by specifying the Impedance Magnitude. By default, if a device satisfies the waveform and Impedance Magnitude requirements, it meets the previously specified Real and Imaginary Impedances.

The Primary Master or Analog Controller will usually incorporate a Current Sense Resistor and may AC couple the Digital Signal. To allow maximum flexibility, there is no specification of how this should be done.

The bandwidth during receive is adequately addressed through the requirements on cable length and Network Resistance. The bandwidth requirement during transmit is automatically satisfied by requiring the transmit resistance to be less than or equal to the receive resistance.

Excessive signals applied to long lengths of multi-pair cable can cause unacceptable master-to-master coupling. The excessive signals are prevented through a combination of transmitted waveform requirements and the impedance requirements.

The Low Impedance Device impedance specification permits flexible arrangements for sensing both Analog Signaling and Digital Signaling. The circuit of Figure 31, for example, develops an Analog Signal for a chart recorder across the series loop impedance 250 Ω and 10 μF combination, a filtered Analog Signal (1-5 volt) for an A/D converter across the 250 Ω in parallel with the 20 kΩ resistor and 10 μF capacitor, and a HART Digital Signal across the 250 Ω resistor.

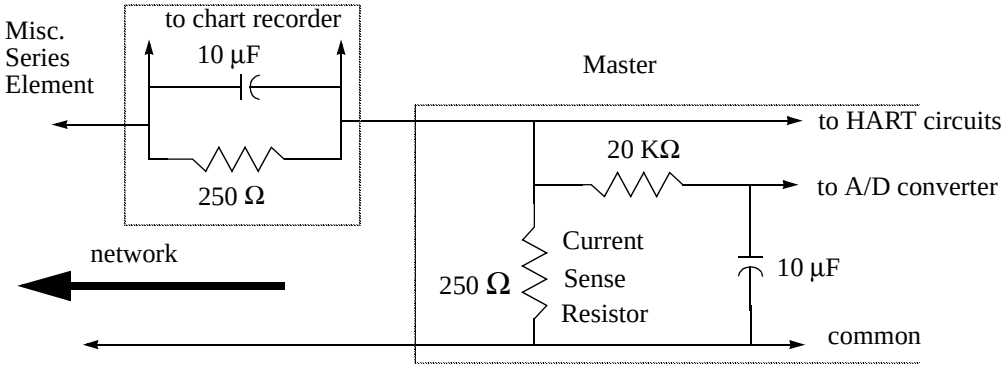


Figure 31. Primary Master Signal Sensing Arrangement

Over the Extended Frequency Band, Low Impedance Devices can be modeled as impedance combinations as shown below in Figure 32.

Send Impedance = ((Send Z || Receive Z) + Coupling Z) || Sense Impedance

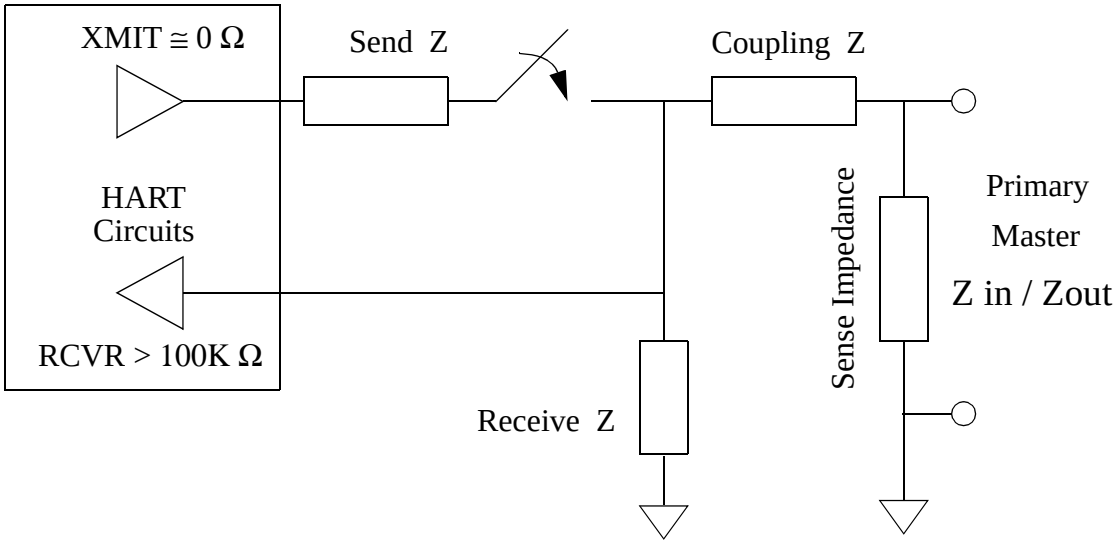


Figure 32. Low Impedance Device Model

Over the Extended Frequency Band, Secondary Devices can be modeled as impedance combinations as shown below in Figure 33.

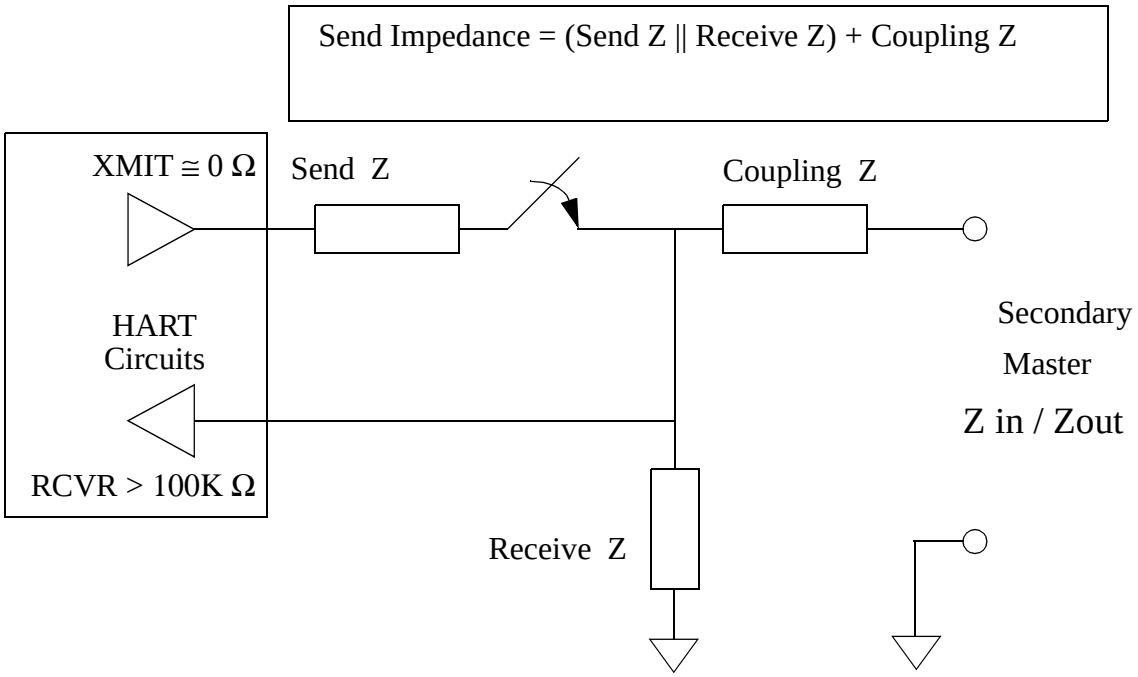


Figure 33. Secondary Device Model

A - 7.3.1.3 Secondary Device Impedance

A secondary device by definition is temporarily connected. The impedance requirements are intended to simply keep it's effect at or below the level assumed in the network length formulas, so the user need not take any Secondary device separately into account in a network analysis. With the impedance magnitude above the 5 kΩ minimum, the reactive component will not significantly affect the network properties.

A - 7.3.2 Interference to Analog Signaling

In previous specifications, a figure has been provided which depicted the analog output frequency spectrum limits as having a maximum amplitude of 16 mApp (full-scale 4 - 20 mA signaling) and a 40 dB/decade roll-off starting at 25 Hz. The Rev. 7.2 Physical Layer Specification further stipulated that a 2-pole analog filter with poles at 25 Hz was sufficient to limit the frequency spectrum of a 16 mA square wave so it would not interfere with communications.

The initial release of Rev 8.0 of this document contained stated limits of 924 mA/s slew rate and 52 uA step size, in addition to the analog signaling bandwidth diagram. Those stated limits are not sufficient to guarantee that an analog output meets the bandwidth limitations; other parameters such as reversal characteristics and update rate affect the bandwidth and hence the results. The present speci-

fication omits reference to those limits to avoid misleading the reader to conclude that they are sufficient.

The additional requirement that the device be capable of successful communication (bit error rate < 1 in 10,000) during worst-case analog signaling with the received HART signal attenuated to 130 mVpp amplitude, is stated to ensure that the design has allowed for worst-case signaling in its own sending and receiving circuits.

A - 7.3.2.1 Carrier Start/Stop

For the purposes of this specification, the worst-case analog signal input, in terms of transient susceptibility, is assumed to be one with a 2-pole 25 Hz low-pass filter on the analog signal. It is also assumed that the current sense resistance for such current receiving devices is 250 Ω . With these assumptions, it is desired to keep the worst-case effect of a transient below 0.25% of the analog signal. A 4 - 20 mA signal through a 250 Ω resistance generates a signal of 4 V. 0.25% of 4 V is 0.010 V. This limit represents a compromise between practicality of implementation and minimized impact on process control.

Recognizing that this specification is tighter than in previous HART Physical Layer Specifications, the footnote to this section provides an allowance for devices to exceed the new recommended limit, if designed with a modem that makes compliance impractical, or if designed prior to release of this specification.

CAUTION: The old specification made an erroneous claim that its limit would keep analog signal interference by transients to less than 0.025%. Simulation has shown that the old limit could allow up to 0.75% momentary effects to get through the assumed worst-case input filtering. Compliance with the tighter specification is highly recommended in order to keep the potential for interference to analog signalling at a reasonable minimum.

Derivation of the 0.75% possible effect from the old limit:

The old specification (revision 8.0) had 2 normative requirements: (1) The average voltage of the transient over 10 ms shall not exceed 50 mV; (2) The transient shall decay to half or less of its original value within 10 ms.

The second requirement (decay to half initial value) translates to a 14.4 ms maximum time constant of the decay. It was determined that with this slow of a decay, the initial transient value had to be 69.3 mV or less.

For the other worst-case, it was assumed the maximum value of an on/off transient would be half of the maximum signal value (which is now 800 mV) or 400 mV. With a 400 mV starting point, the decay time constant had to be no longer than 1.25 ms to meet the old specification.

For an intermediate example, a 0.116V initial value with a 5 ms time constant also just met the requirements.

These 3 transients were simulated and fed into a 5 Hz low-pass filter as mentioned in the old specification appendix, and it was found that the output of the filter was about 16 mV in one case and about 14 mV in the other. (Not 2 mV as claimed by the old appendix.)

Given that the transient could be coming from a voltage signalling device, and that the sense impedance in a loop is normally 250 Ω or smaller, 16 mV is likely to be 0.4% of span.

The same transients were also simulated into a 2-pole 25 Hz filter instead of the single-pole 5 Hz. Given that controllers are getting faster, and given that the HART specs identify this as the analog signalling spectrum, it was thought that this is actually more realistic than the single-pole. In that case, one of the allowable transients produced as much as a 30 mV filter output... that's 0.75% of span.

A - 7.3.2.3 Cyclic Connection Transients

To prevent interference from the connection or disconnection of a Current Input or Secondary device, the device should not be capable of sinking or sourcing a significant amount of current to cause interference with analog signaling. A common cause of sinking current is a device that uses too large of a coupling capacitor unto the network without limiting the current flow into it.

A - 7.3.3 Output During Silence (Interference on Digital Signaling)

The received Digital Signal will normally be corrupted by some amount of noise, coupling, and possibly Analog Signaling (which includes so-called process noise). The noise consists of Network Power Supply noise, illumination of the HART cable by EMI, and the noise generated by each of the "silent" Signaling Elements.

Noise from silent Signaling Elements can either be broadband random noise or correlated noise existing at a few discrete frequencies. The combined noise would be measured, for example, by an oscilloscope preceded by a filter passing only the Extended Frequency Band. The assumption that correlated noise from various devices will add in RMS fashion is strictly true only when there is no frequency and phase relationship between noises from different devices. The alternative is to assume that there is a relationship and to force the noises to be added linearly. This, however, would be unrealistic and would lead to exceedingly small values for the noise specification.

In a Point-to-Point Network, Analog Signaling interference can be present, whereas broadband or correlated noise from a large number of silent devices usually will not be. In a Multi-Dropped Network, broadband noise from a large number of silent devices may be present. With coupling and EMI added there are clearly too many possible combinations of noise and interference to consider each one separately.

Instead, a reasonable approach is to assume that each type of noise or interference by itself should yield a signal-to-noise ratio of no less than 14 dB. Additionally, Analog Signaling interference and noise in Multi-Dropped Networks should not be simultaneously included. These assumptions produce 3 sources:

1. Analog Signaling Interference or Multi-Dropped silent device noise.
2. EMI.
3. Coupling.

The minimum signal at the Primary Master or Analog Controller is known to be 130 mV p-p or about 46 mV RMS. If the noise from silent devices and the Network Power Supply is to be 14 dB below this, there can be no more than 9.2 mV RMS of noise. If this is divided equally among 17 possible Signaling Elements and one Network Power Supply, then each source should be under 2.2 mV RMS.

A Transmitter signals as a current source. Therefore its noise is a current. The 2.2 mV of acceptable noise per element divided by the 500 Ω test load yields 4.4 uA RMS.

By stating that the noise of silent devices applies over the Extended Frequency Band, the requirements on receiver circuits are reduced. Simpler filtering is possible, compared with the case in which the same amount of noise is specified over a smaller band.

A - 7.4.1 Test Loads

It is recommended that all devices be tested for conformance to the specification under worse case test load conditions.

For example, a high impedance device may have a conformant waveform with a 500 Ω load, but in reality when connected to a 250 Ω current sense resistor may have a waveform with distortion and/or attenuated amplitude. Any nonconformance in waveshape may effect the distance a HART device can reliably communicate.

As it is pointed out in section 7.4.1, it may be necessary to add a series 100 uF capacitor to the resistive test load to DC block any current through the test load that may upset the operating parameters of the device under test.

In some cases it may be appropriate to place the test load in series with the test device rather than across the device’s terminals.

A - 7.5.1 Cable Types

If single-pair and multiple-pair cables are mixed in a given Network, there should be only a single length of multi-pair. This single length of multi-pair should connect to the Primary Masters. This follows conventional practice in which a multi-pair home run cable connects a controller to a junction box in the field area, and a single-pair cable connects each Field Instrument to the junction box.

A - 7.5.2 Recommended Minimum Conductor Size (Diameter)

The size (gauge) specification has to do with Field Instrument Analog Signaling voltage. This voltage is developed at the Field Instrument terminals due to the analog current variation multiplied by the sum of the Network Resistance and cable resistance. As the conductor diameter becomes smaller, cable resistance goes up, leading to excessive voltage variation at the Field Instrument terminals due to Analog Signaling. Excessive voltage variation can interfere with digital signal reception (Section 7.3.2).

The Network Resistance is specified elsewhere to be 600 Ω or less. It is desirable to keep the cable resistance small compared to this. A 5000 ft. (1500 meter) length of #24 cable will have a resistance of about 260 Ω (both halves of pair included), which is sufficiently small. A 10,000 ft. (3000 meter) length of #20 has less than 260 Ω.

A - 7.5.3 Calculated Single-Pair Length

Variables

R_P Parallel Network Resistance.

The parallel combination of the Rx values of all connected devices whether signaling or not (including parallel-connected miscellaneous impedances).

R_S Series Network Resistance.

The series combination (simple addition) of all series resistances in the network including wiring resistance, Barrier resistance, and miscellaneous other series resistances.

C_D Device Capacitance

The parallel combination (simple addition) of the Cx values of all network devices i.e. the worst-case Ct-t of all connections to the loop whether they communicate or not (including parallel-connected miscellaneous impedances).

C_W Wiring Capacitance

The sum of all the capacitance of all the wire connected to the loop.

C_N Network Capacitance

The parallel combination (simple addition) of all network capacitances including device capacitances, wiring capacitances, and miscellaneous capacitances.

Limits imposed by the 65 μs rule

Figure 34 below depicts the limits on capacitance in a HART loop due to the 65 μs rule, i.e. that the network resistance multiplied by the total network capacitance shall not produce a time constant longer than 65 μs. This rule is intended to keep the time constant of the network above the signaling frequencies such that there is not a significant distortion of the signal nor a significant attenuation of the higher signaling frequency (2200 Hz) due to network capacitance. If we assume that this requirement is to be met at all points on the network, not just at the lowest impedance point, we must add any series network resistances to the combined parallel resistances to determine the R to be used for the time constant. Similarly, we add all the parallel capacitances (all individual devices + wiring capacitance) to determine if the network is within the specified limit. Note that the formula subtracts 0.0032 from the total allowable capacitance to take into account the connection of a Secondary Device. The specification limiting the capacitance of a Secondary device is the 5 kΩ min. impedance magnitude. For the purposes of this rule, the parallel resistance of the Secondary device is assumed to be high enough that it's effect is negligible.

The formula for determination of the allowable Network Capacitance is:

$$C_N(uF) \leq \left(\frac{65}{(R_P + R_S)} - 0.0032 \right)$$

Note that the allowable network capacitance cannot be directly converted to allowable length because wiring adds series resistance as well as capacitance. This will be discussed in a later section.

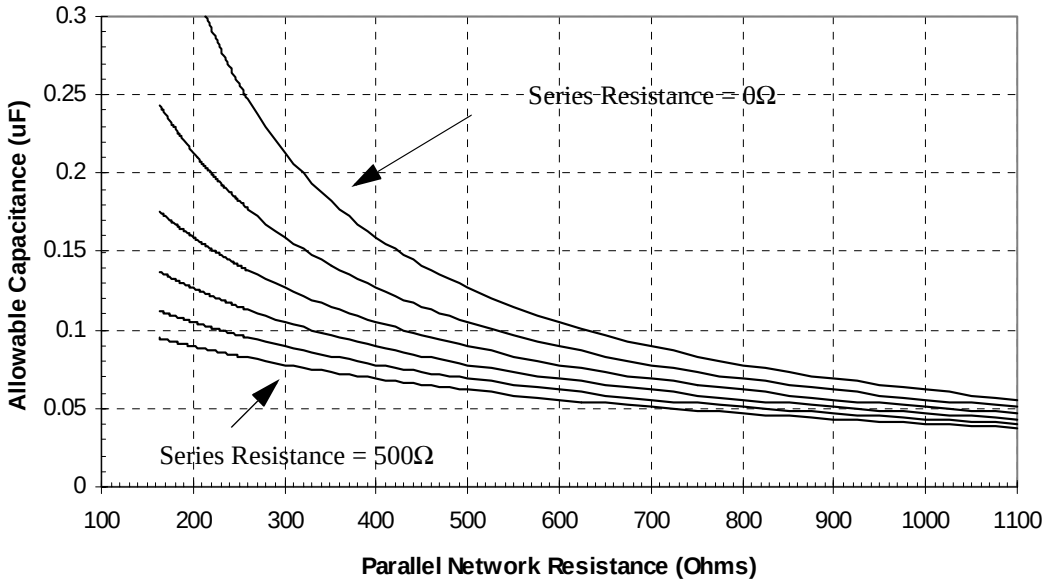


Figure 34. 65 μs Rule Capacitance limits

Limits imposed by the minimum amplitude with current signaling

It is necessary for the amplitude of the HART signal to stay above 120 mV at all devices for proper reception. The length calculations are derived from an assumed minimum of 130 mV to allow a 10 mV margin for unanticipated effects. One way for HART devices to generate the HART signal is to modulate the loop current. This is most common in the case of devices that also control the analog current i.e. a common transmitter. The worst-case combination of network resistances in the case of a current signaling device is as shown below in Figure 35:

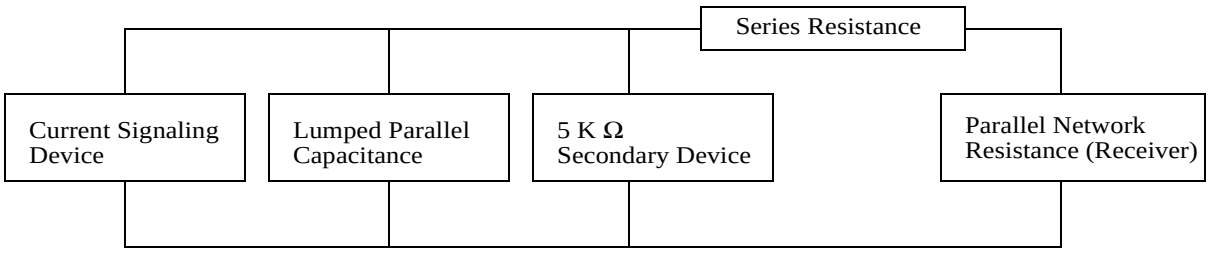
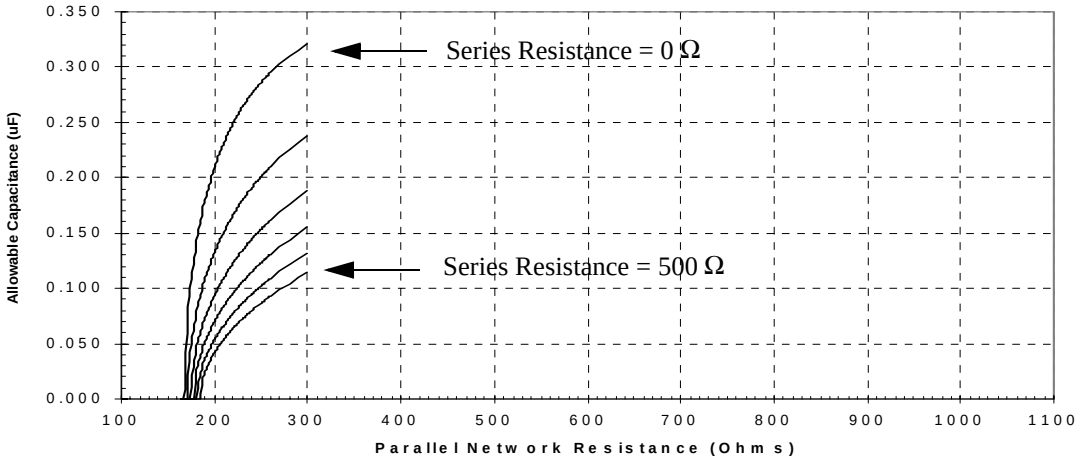


Figure 35. Worst-Case Combination of Network Resistances; Current Signaling

If the parallel network resistance is greater than about 230 Ω , the 65 µs rule will keep the capacitance small enough to assure adequate signal amplitude at all points on the network. However, if the parallel network resistance is smaller than 230 Ω the 65 µs rule allows capacitance values that would produce inadequate signal amplitude at the low impedance point on the network. Figure 36 depicts the capacitance limits produced by the amplitude requirement given the network above and the R_P and R_S values shown. Note that the formula and the chart take into account the presence of a Secondary device so the user need not include that in his Parallel Resistance calculation.

The formula for determination of the allowable Network Capacitance is:



$$C_N(uF) \le 63.662 \times \sqrt{\left(\frac{0.006154 \times R_P}{R_P + R_S}\right)^2 - \left(\frac{1}{R_P + R_S} + \frac{1}{5000}\right)^2}$$

Figure 36. Signal Amplitude Capacitance Limits; Current Source

Limits imposed by the minimum amplitude with voltage signaling

As stated earlier, it is necessary for the amplitude of the HART signal to stay above 120 mV at all devices for proper reception. The length calculations are derived from an assumed minimum of 130 mV to allow a 10 mV margin for unanticipated effects. Another way for HART devices to generate the HART signal is to modulate the loop voltage. The worst-case combination of network resistances in the case of a voltage signaling device is as shown below in Figure 37:

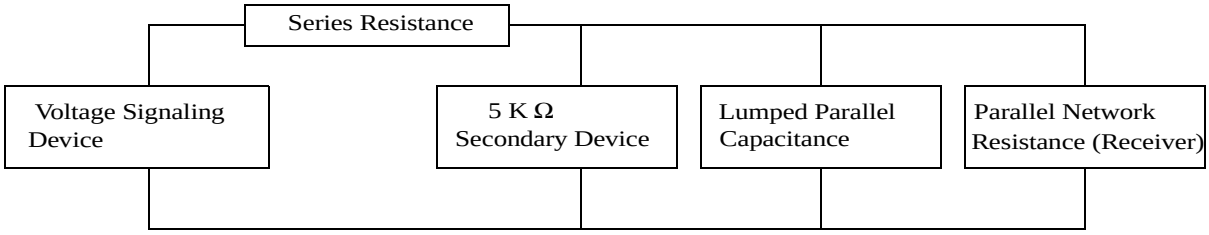


Figure 37. Worst-Case Combination of Network Resistances; Voltage Signaling

If the series network resistance is less than about 350 Ω , or the parallel network resistance is greater than about 250 Ω , the other rules will keep the capacitance small enough to assure adequate signal amplitude at all points on the network. However, if the series network resistance is larger than 350 Ω, the parallel resistance and capacitance limits will be affected. Figure 38 below depicts the resistance and capacitance limits produced by the amplitude requirement given the network above.

The formula for determination of the allowable Network Capacitance is:

$$C_N \leq 63.662 \times \sqrt{\frac{9.467}{R_S{}^2} - \left(\frac{1}{R_S} + \frac{1}{R_P} + \frac{1}{5000}\right)^2}$$

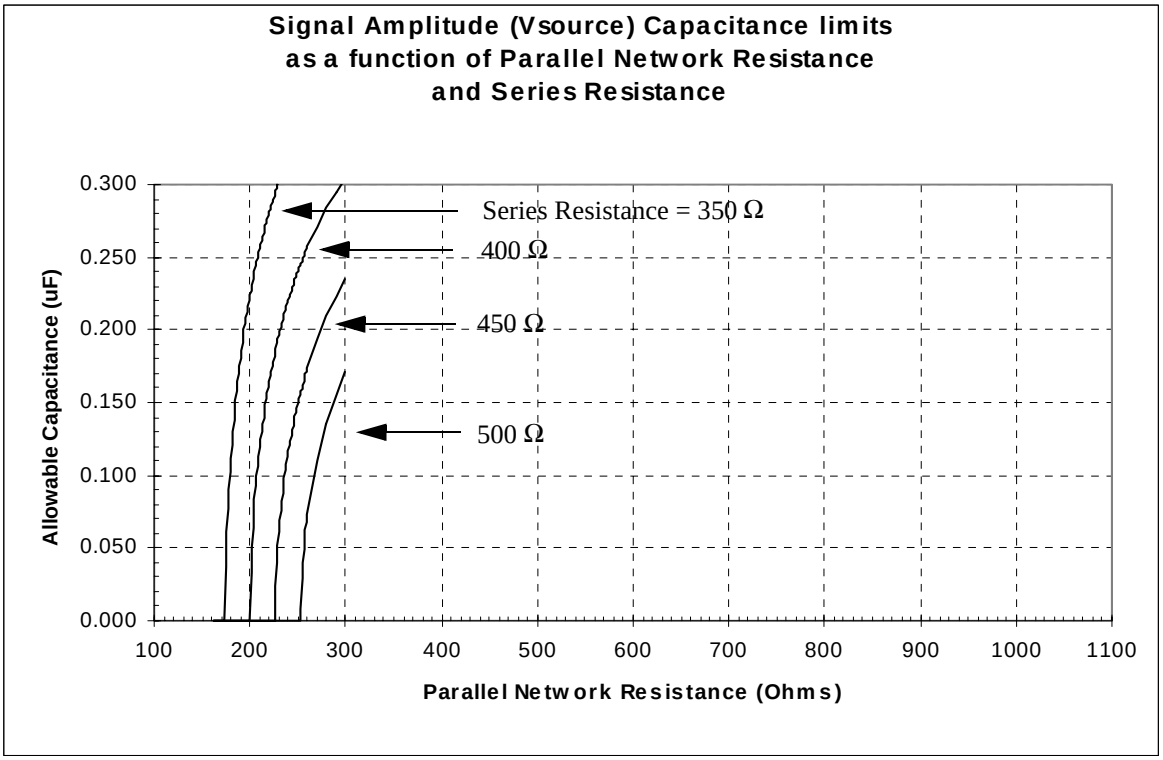


Figure 38. Signal Amplitude Capacitance Limits; Voltage Source

Network Length Determination

The three formulas just presented give a result of allowable capacitance on the network assuming resistance values. Unfortunately, allowable capacitance is not enough for a direct length determination because cable also has series resistance. It is possible to iteratively determine the allowable length from network parameters as follows:

1. Use the formulas to determine an allowable capacitance.
2. Subtract the capacitance of connected devices Cd.
3. Assume the remaining capacitance is cable and calculate the length from known cable parameters.
4. Determine the resistance of that length from cable parameters.
5. Assume that resistance is present as a series resistance and go back to 1.
6. Repeat the iteration until the change between iterations is insignificant.

This would be a very tedious process. To prevent the user from having to do this, a number of such iterative calculations were done with known values to produce the charts shown in Figure 19 through Figure 23 in Section 7.5.3, and additional charts showing the effects of miscellaneous series resistance in Figure 39 through Figure 51 in Annex B.

While the assumptions that have gone into the calculations are worst-case and therefore conservative, they also perhaps oversimplify the effects of reactive components. One should not expect that the cable length at which communications stop working will exactly match what's predicted with this method, but rather that this provides a general guideline for the user to follow when choosing cable types and planning HART networks.

A - 8.1 Network Power Supply

In practice the Network Power Supply and Analog or Primary Master may be contained on the same circuit card. For clarity in defining the various parts of the HART Network, they are shown as separate.

The requirement that the Barrier and Network Power Supply allow for superposition of a 1.4 volt p-p signal is necessary to prevent the Barrier zener diodes from being biased on by the superimposed HART signal. This might happen for example if the transmitter Analog Signaling current were to drop to 4 mA in a system with a supply-side Current Sense Resistance, or increase to 23 mA in a system with a return-side Current Sense Resistance. The value is derived as follows:

Primary and Secondary Masters signal as voltage sources. Their maximum output is specified as 0.6 volt p-p. The most voltage that they can superimpose on the Network Power Supply voltage is 0.3 volt. Field Instruments signal as current sources, with 1.2 mA p-p maximum current. We require that the Current Sense Resistance be not more than 600 Ω . Therefore, the Field Instrument can superimpose at most 0.66 volt peak on to the Network Power Supply voltage. The specified value of 0.7 volt peak is the larger of the master versus Field Instrument signals or 0.66 volt with a small margin added.

The 0.66 volt is actually an upper limit. Elsewhere it is required that the Network Resistance, can't exceed 600 Ω . This implies that, with a Barrier present, the Current Sense Resistance must be under 600 Ω . Therefore, 0.66 volt peak cannot be produced by the signal.

The 0.7 volt peak value is a compromise between ease of specification and keeping the voltage as small as possible. A variety of special cases, each requiring a separate analysis, would otherwise result. With the combined Barrier and Network Power Supply requirements presented in this way, users can continue to use DC calculations to determine acceptable loop voltage drops.

A - 8.1.2 Shielding and Grounding

The requirement for single point Grounding of the shield is to avoid pickup of magnetically coupled interference, which tends to be easily coupled at HART signaling frequencies.

A - 8.2 Barriers

When a Barrier is present, the impedance presented to the Network will depend on both the Barrier and on the master attached to the safe (non-Network) side of the Barrier. For example, the end-to-end resistance of a passive, conventional zener barrier may increase if the master resistance is decreased so that the total remains under 600 Ω. In cases where the Barrier and master are supplied by different vendors, these vendors may find it useful to publish lists of compatible combinations.

For transmission from hazardous side to safe side, there are two tests for attenuation. This establishes the capability of the Barrier to transmit signals from either a Field Instrument or a Secondary Master to the Primary Master.

A - 8.3 Miscellaneous Hardware

Connection of additional hardware in series with the Network Power Supply must be avoided. Too high an impedance in series with a power supply that serves multiple Networks can otherwise result in interference between Networks.

ANNEX B. WIRE RESISTANCE TABLE

The following Table provides the resistance of copper wire for various AWG sizes. The associated wire resistance is used in the length calculations and is described in Section 7.5.3.

Table 13. Wire Resistance Table

Wire Size (AWG)	Resistance/ ft.	Resistance/ meter	Wire Size (mm^2)	Resistance/ meter
16	0.0040 Ω	0.013 Ω	0.5	0.0368 Ω
17	0.0050 Ω	0.016 Ω	0.75	0.0265 Ω
18	0.0064 Ω	0.021 Ω	1.0	0.0184 Ω
19	0.0080 Ω	0.026 Ω	1.5	0.0123 Ω
20	0.010 Ω	0.032 Ω		
21	0.013 Ω	0.042 Ω		
22	0.016 Ω	0.052 Ω		
23	0.020 Ω	0.066 Ω		
24	0.026 Ω	0.085 Ω		
25	0.032 Ω	0.10 Ω		
26	0.041 Ω	0.13 Ω		
27	0.051 Ω	0.17 Ω		
28	0.065 Ω	0.21 Ω		
29	0.082 Ω	0.27 Ω		
30	0.100 Ω	0.33 Ω		

B1. Additional Cable Length Graphs

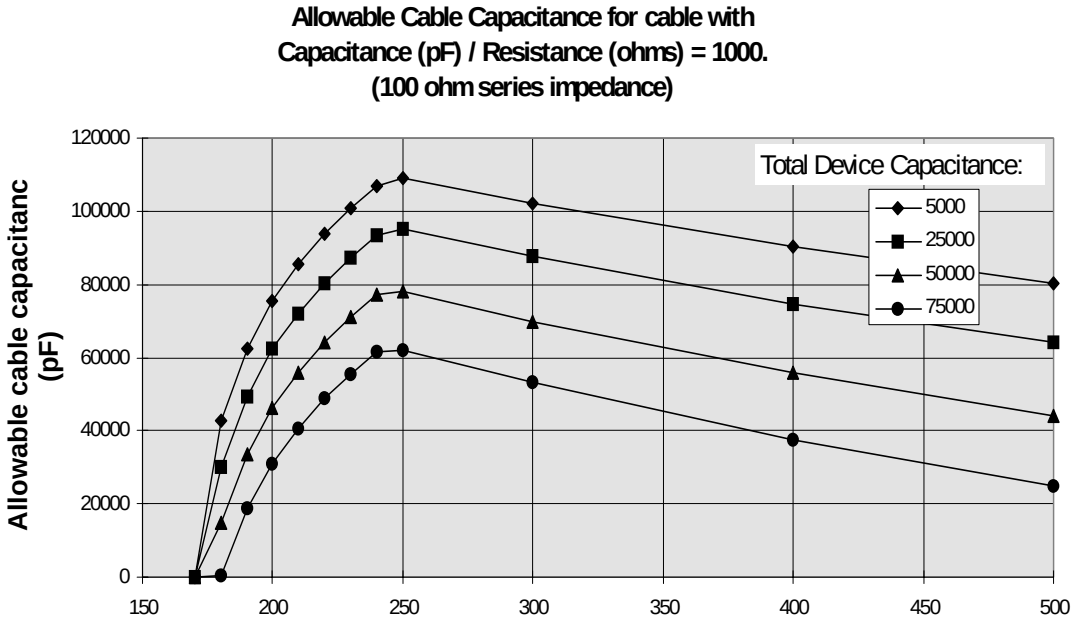


Figure 39. Capacitance/Resistance = 1000; 100 Ω Series Resistance

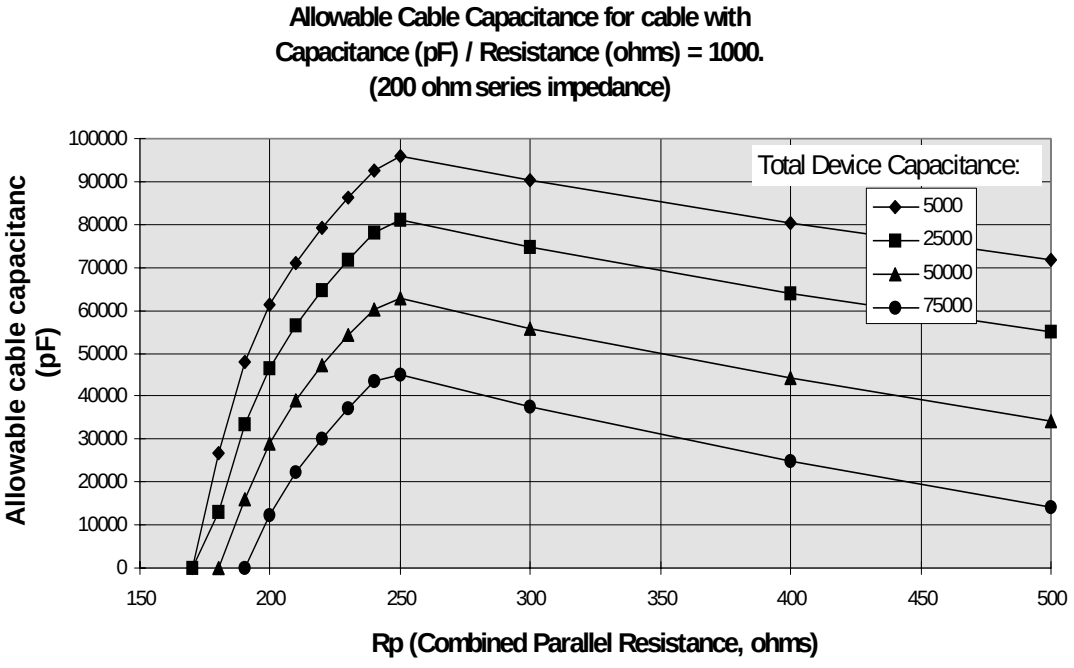


Figure 40. Capacitance/Resistance = 1000; 200 Ω Series Resistance

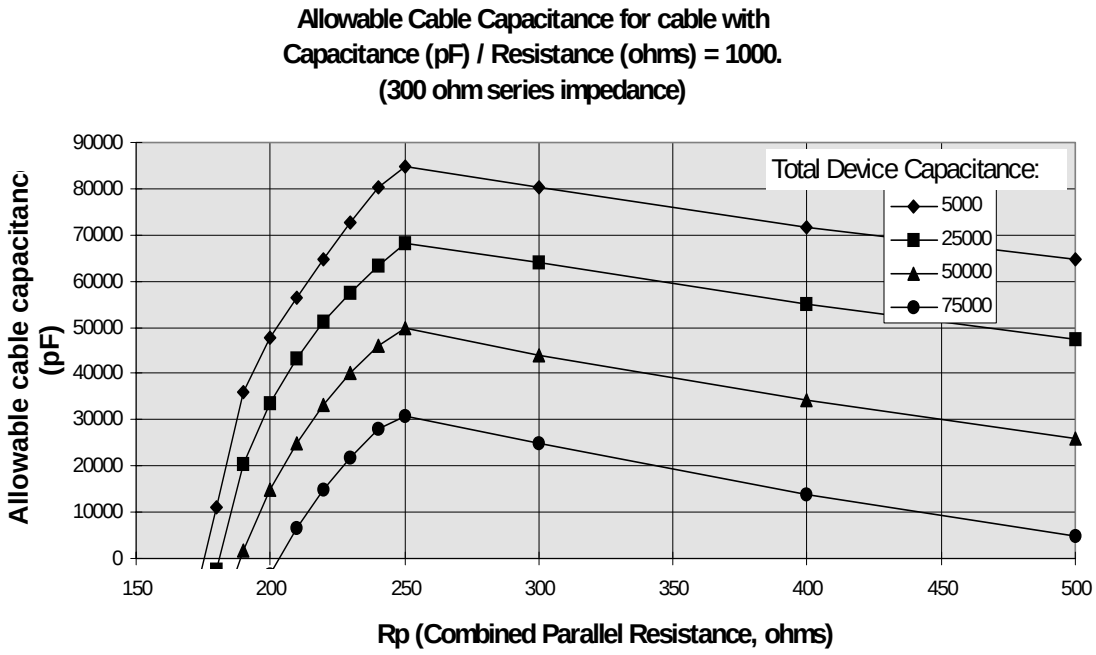


Figure 41. Capacitance/Resistance = 1000; 300 Ω Series Resistance

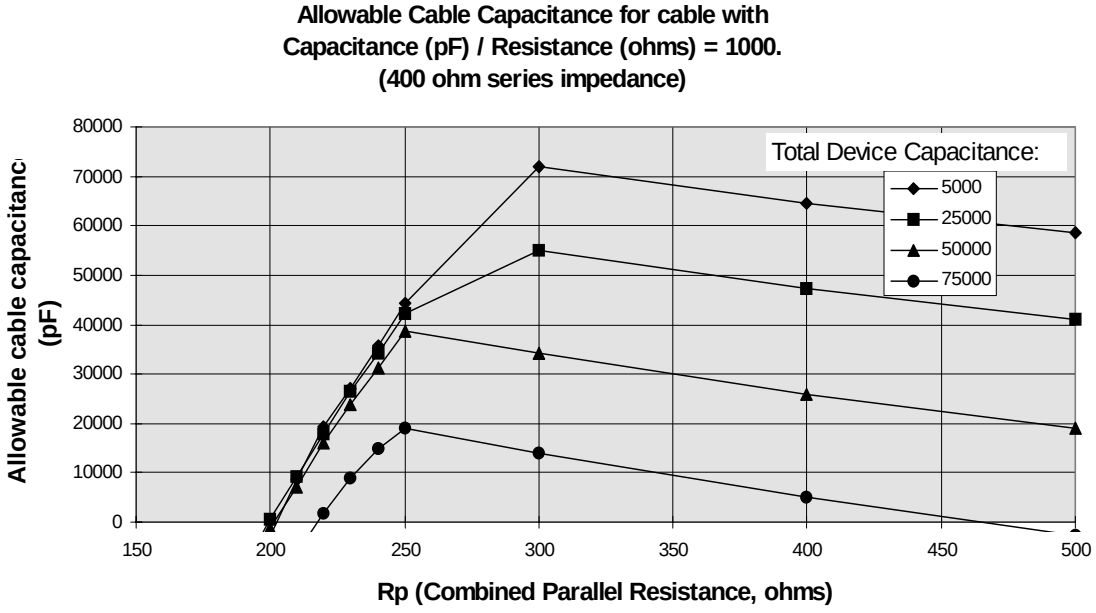


Figure 42. Capacitance/Resistance = 1000; 400 Ω Series Resistance

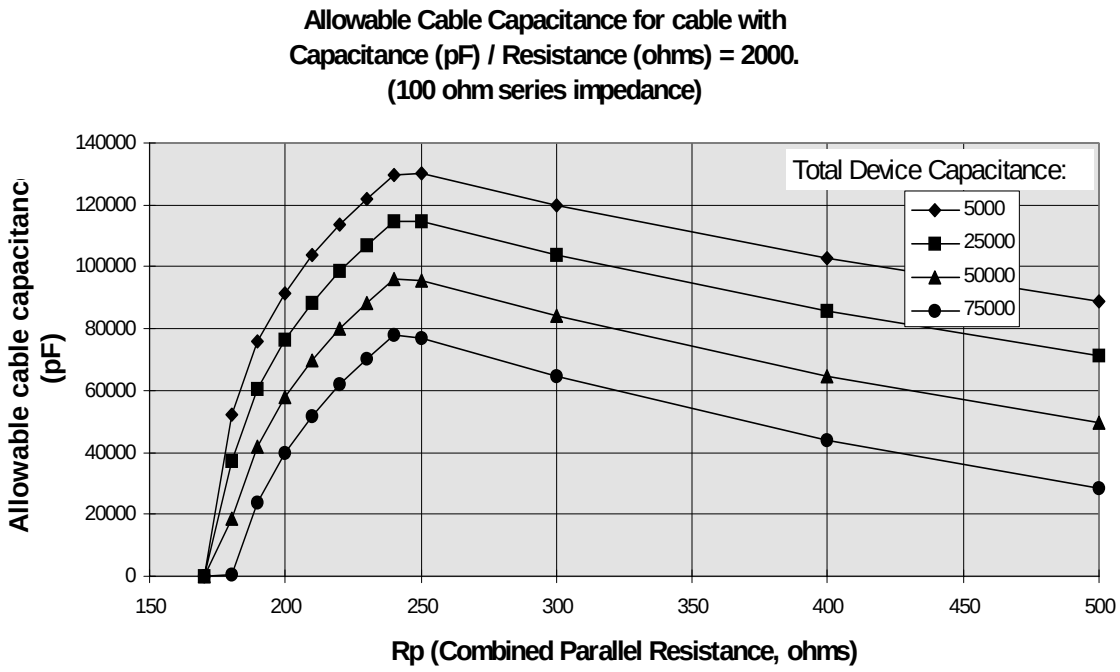


Figure 43. Capacitance/Resistance = 2000; 100 Ω Series Resistance

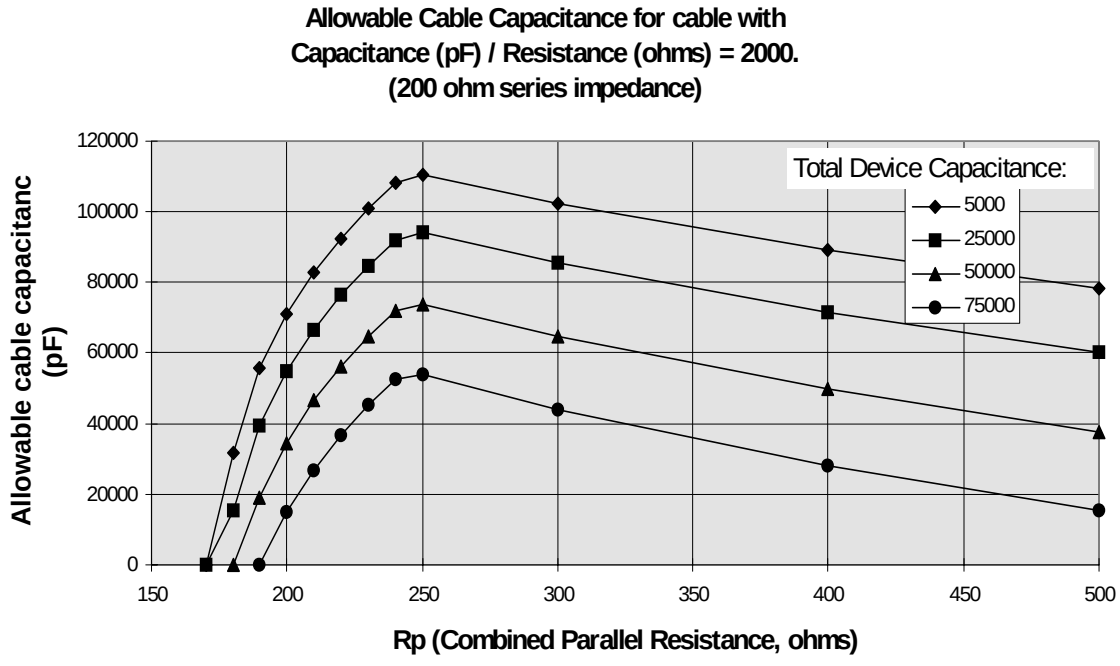


Figure 44. Capacitance/Resistance = 2000; 200 Ω Series Resistance

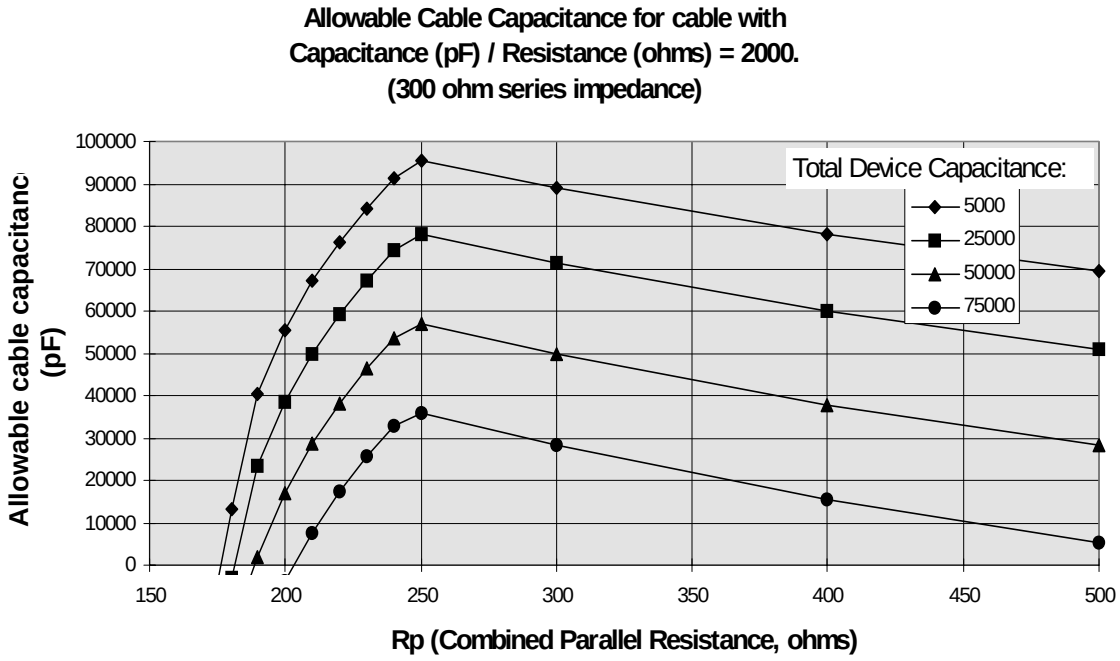


Figure 45. Capacitance/Resistance = 2000; 300 Ω Series Resistance

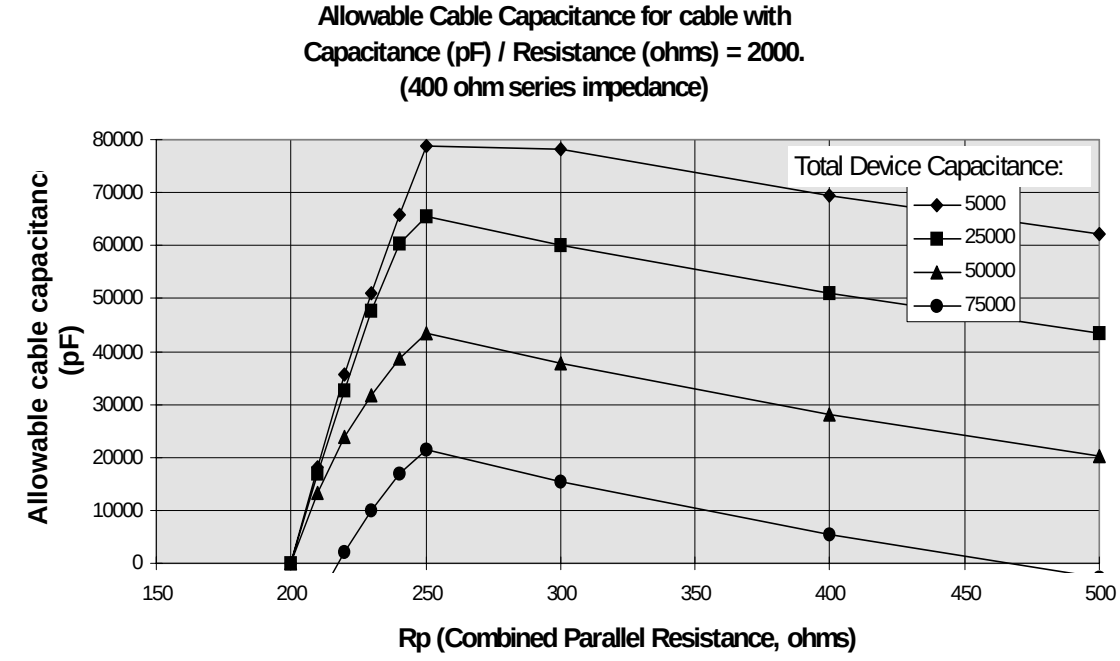


Figure 46. Capacitance/Resistance = 2000; 400 Ω Series Resistance

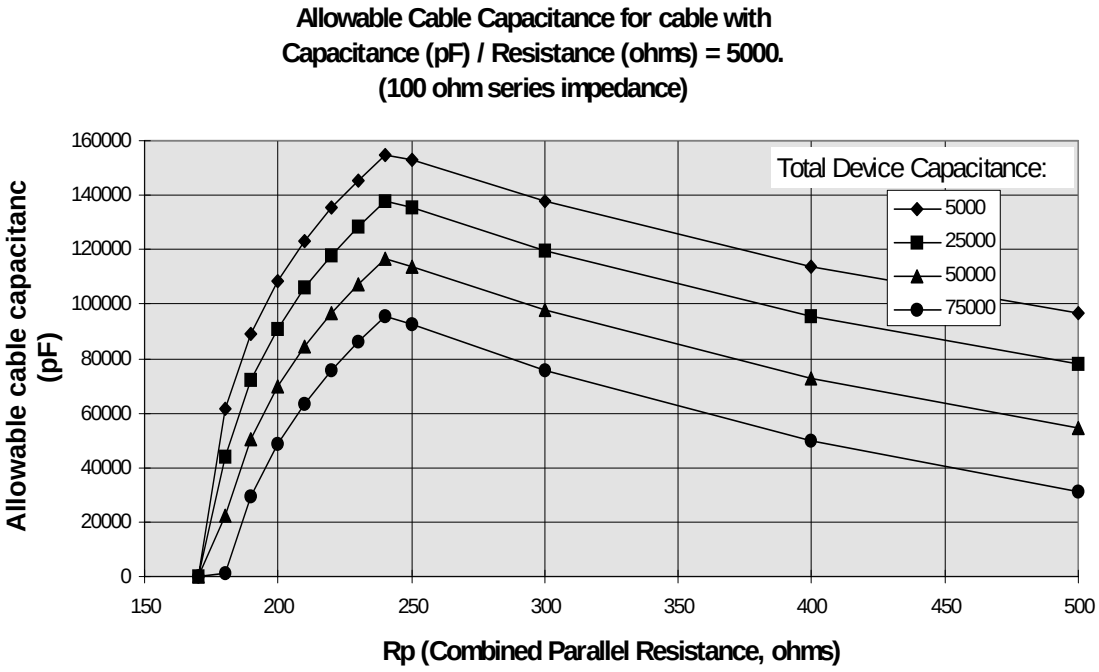


Figure 47. Capacitance/Resistance = 5000; 100 Ω Series Resistance

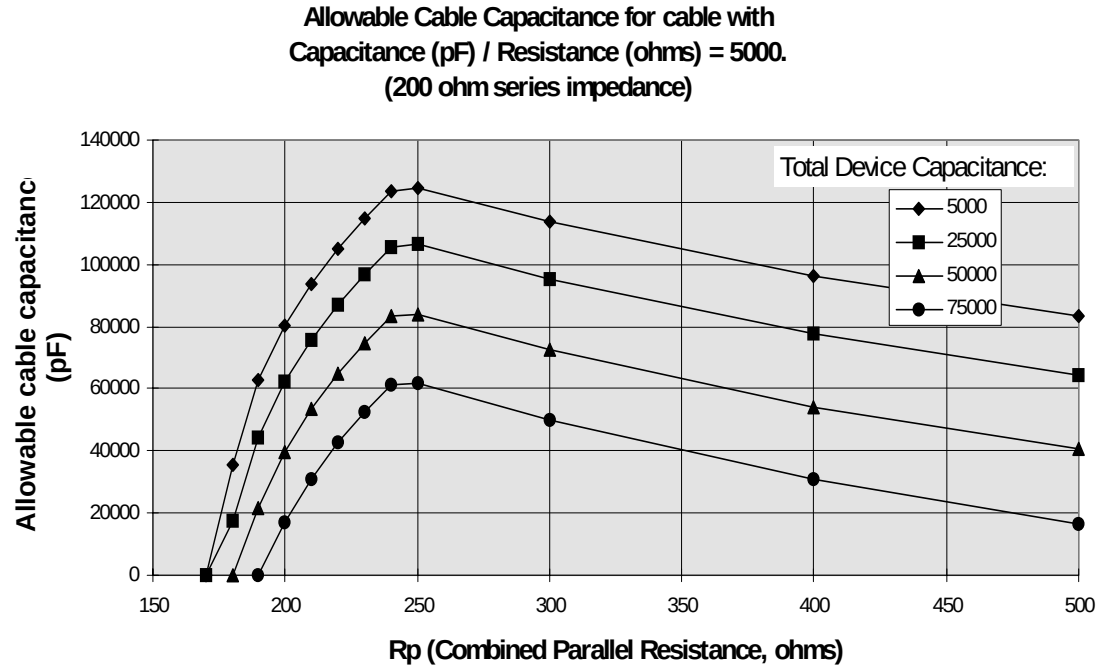


Figure 48. Capacitance/Resistance = 50000; 200 Ω Series Resistance

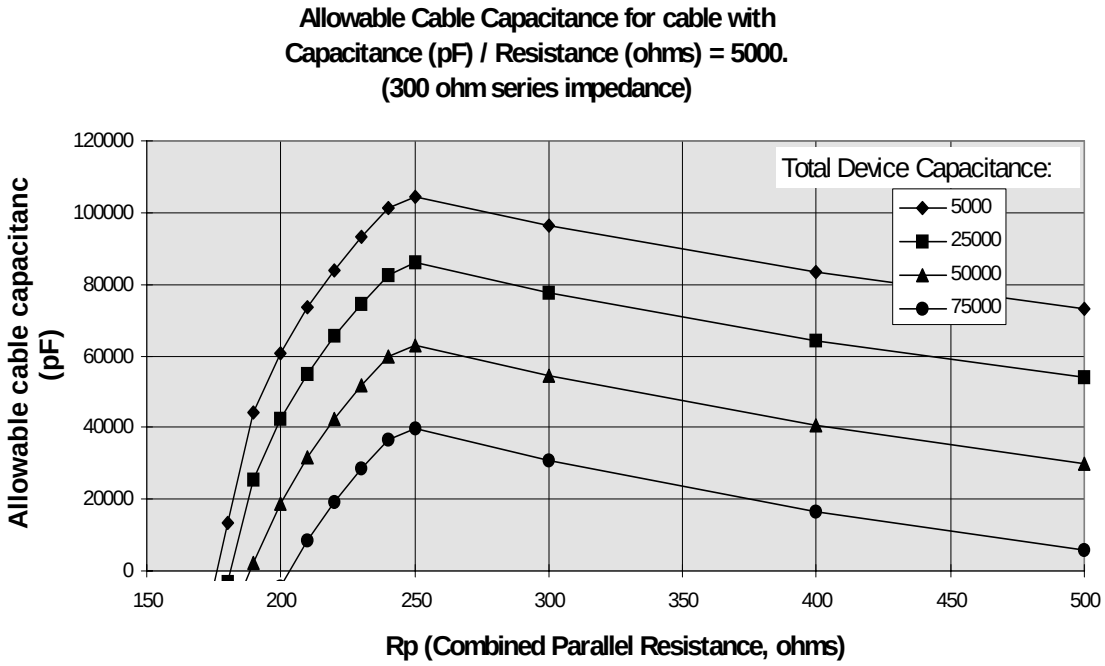


Figure 49. Capacitance/Resistance = 5000; 300 Ω Series Resistance

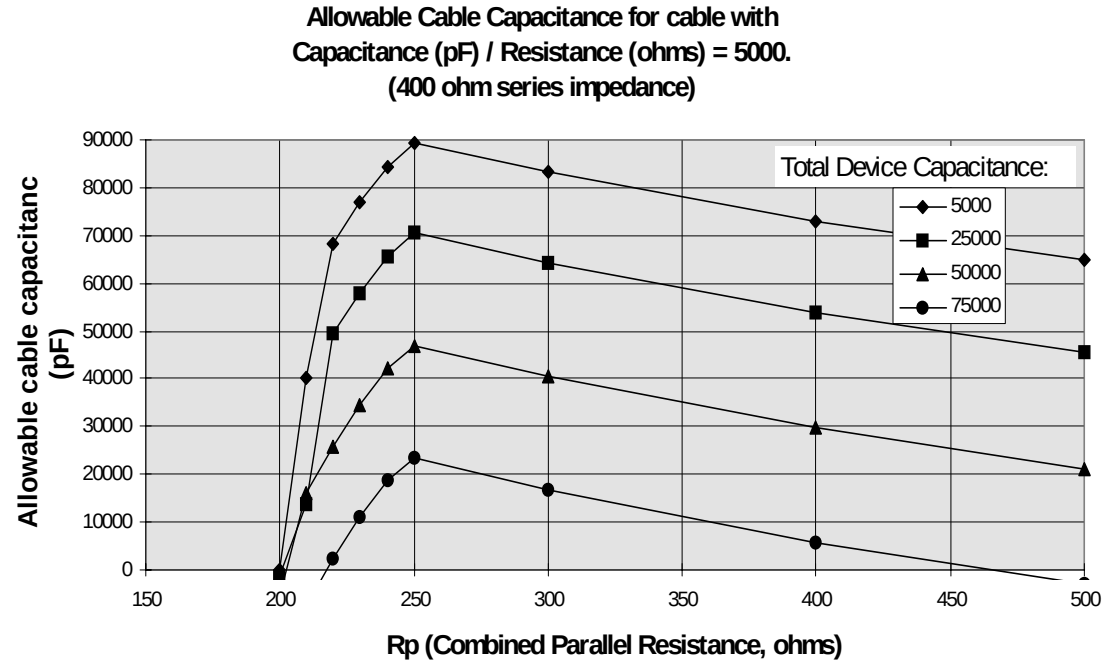


Figure 50. Capacitance/Resistance = 5000; 400 Ω Series Resistance

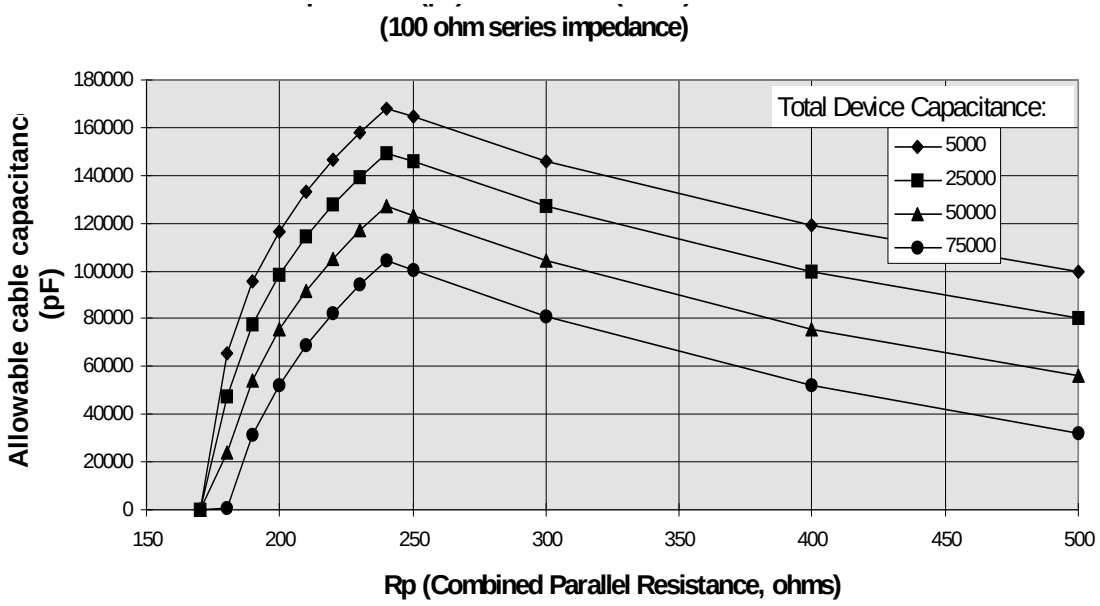


Figure 51. Capacitance/Resistance = 10000; 100 Ω Series Resistance

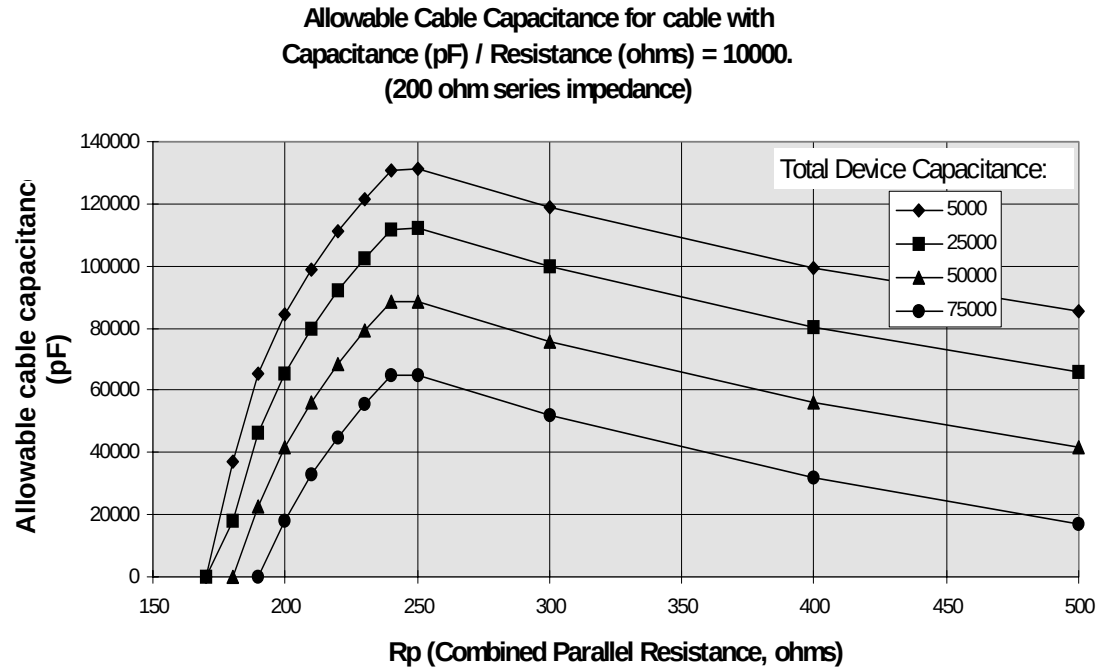


Figure 52. Capacitance/Resistance = 10000; 200 Ω Series Resistance

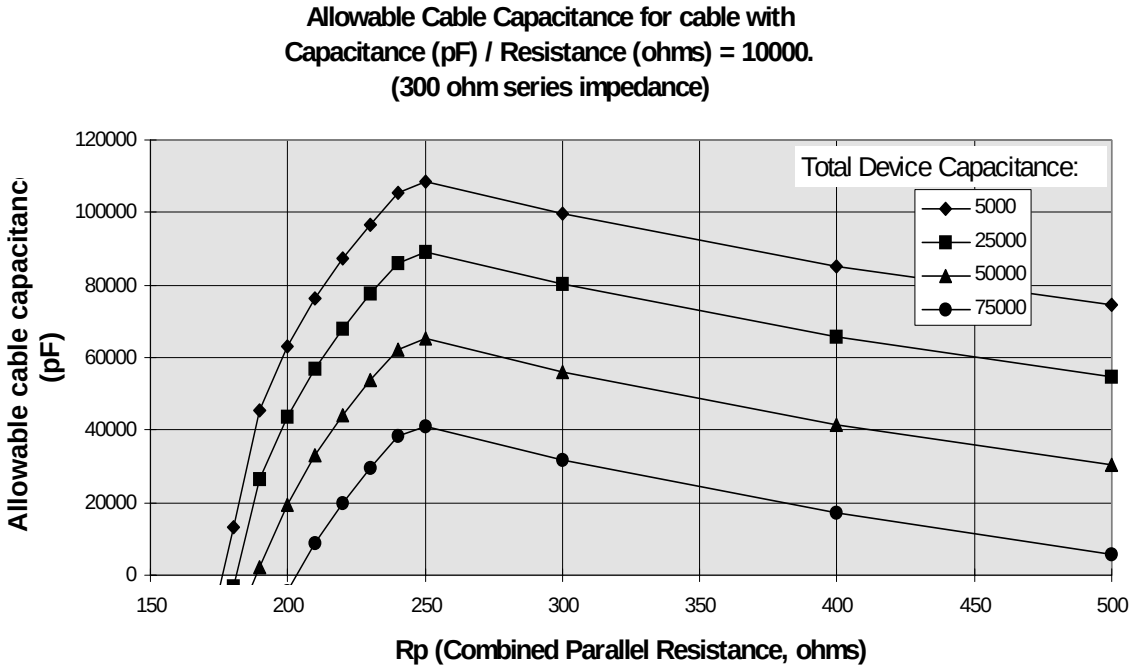


Figure 53. Capacitance/Resistance = 10000; 300 Ω Series Resistance

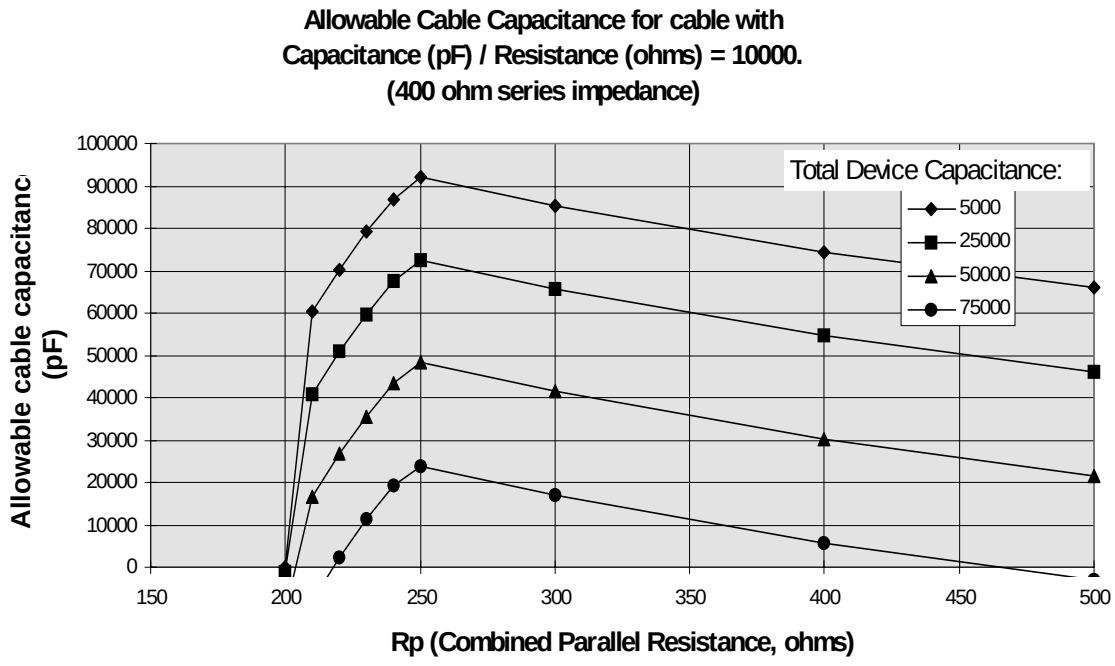


Figure 54. Capacitance/Resistance = 10000; 400 Ω Series Resistance

ANNEX C. DOCUMENT REVISION HISTORY

C1. Changes from Rev 8.0 to Rev 8.1

1. Clarified and improved entire specification. Change bars not used since document restructuring is too signifincant to allow electronic comparison.
2. Clarified and improved the Definitions section.
3. Standardized engineering units throughout document.
4. Reformatted section 5. The paragraphs relating to Low Impedance and High Impedance Devices was moved to the begining of Section 5.
5. In paragraph 5.1 - Lowered impedance of low impedance devices (upper limit) from 1100 ohms to 600 ohms. All figures, tables, and calculations were changed to reflect the 600-ohm value. (Paragraph 5.2 in Revision 8.0)
6. In Table 2 - Added Carrier Decay time requirement.
7. Rearranged paragraph order of Section 7.
8. In paragraph 7.1 - Defined Analog and Digital Signaling spectrums and their effects on each other with regards to transients.
9. In paragraph 7.1.3 - Add DC balancing to transmit waveform. (Paragraph 7.2 in Revision 8.0)
10. Tightened carrier start/stop transient requirements in paragraph 7.3.2.1. The Specification allows the use of the previously specified requirement for those devices unable to meet the more restrictive specification. (Paragraph 7.6.1 in Revision 8.0)
11. Revised methods in Section 7.5.3 for Calculating Single-Pair Cable Length. (Paragraph 7.7 in Revision 8.0)
12. In paragraphs 7.4.2 and 7.4.3 - Defined Analog and Digital Test Filters.
13. In paragraph 8.1 - Corrected errors in power supply ripple. (Paragraph 8.1 in Revision 8.1
14. Revised Figure 28 to match filter requirements of 20C15 modem.
15. Improved specification derivations in appendix.