



# **4-20mA Basics and 2-Wire vs. 3-Wire Transmitters**

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## Background

- Prior to the 1950s, control of industrial sites was achieved with pneumatic systems
- 3 psi – 15 psi was used as the standard signal span
  - 3 psi → 0%
  - 15 psi → 100%
  - 3 psi used as a “live zero”
  - < 3 psi considered a fault condition or “dead zero”
- The 4-20mA current loop was developed to emulate the old 3-15 psi pneumatic system

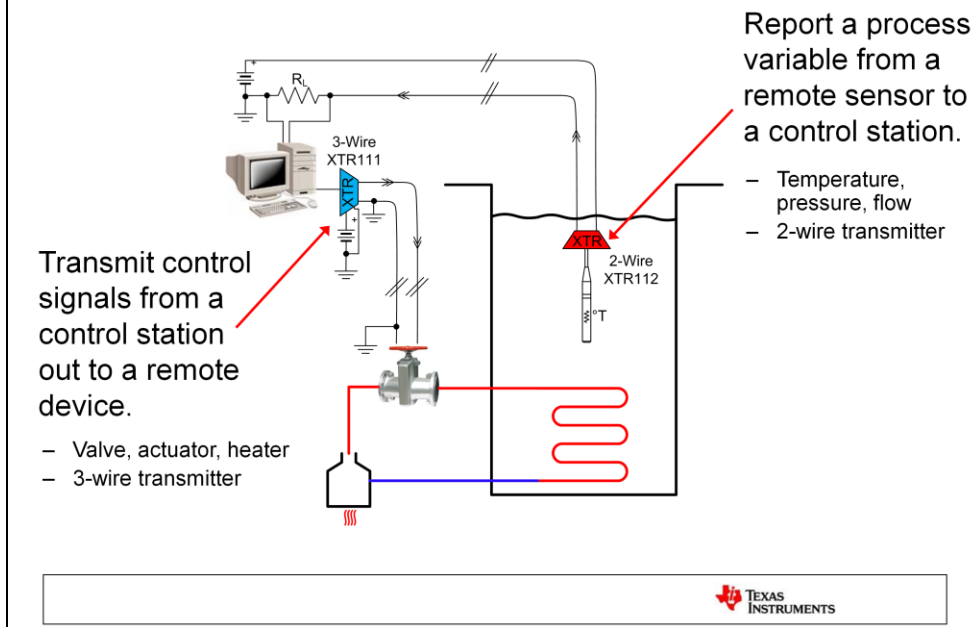


First, a little background.

Up until the 1950s, control of industrial sites was often implemented with pneumatic systems. 3psi to 15psi pneumatic signals were driven throughout a plant by large compressors, and these signals were connected to pneumatically-controlled valves in order to drive proportional controls and actuators throughout the building. 3psi represented 0% of any given variable, while 15psi represented 100%. 3psi was selected as a “live zero,” which allowed levels below 3psi to be treated as a fault condition or “dead zero.”

Once electrical and electronic controls became widely available, the 4-20mA current loop was developed to emulate the 3-15psi pneumatic controls. This method was quickly adopted throughout the industry due to the ease of installation and low power requirements of electrical wires compared to pneumatic pressure lines. Furthermore, electronics allowed for the implementation of more complex control algorithms.

## Typical 4-20mA Applications



4-20mA current loops are primarily used for two purposes:

- 1) To report an industrial process variable such as temperature, pressure, or flow from a remotely-located sensor to a control station. As we will discuss later, the properties of 2-wire transmitters cause them to be best suited for this application.
- 2) To transmit control signals from a control station out to a remote device such as a valve, actuator, or heater. As we will discuss later, the properties of 3-wire transmitters cause them to be best suited for this application.

## 4-20mA Overview



- 4mA represents 0% input level
  - Allows up to 4mA to power external input circuitry
  - 4mA zero level allows under-scale settings and fault detection
- 20mA represents 100% input level
  - Provides sufficient current to power electromechanical devices
  - Over-scale can also be used to detect fault conditions

The typical 4-20mA transmission path is shown here, starting with the sensor on the left. The sensor measures a variable over a specific range, for example, a temperature between 0 and 500°C, and outputs a signal proportional to where the measurement falls within the set range.

The transmitter converts the sensor output to a 4-20mA signal which corresponds to the full scale of the sensor. 4mA represents minimum scale (0°C in our example), while 20mA represents maximum scale (500°C in our example). It then sends this current signal, usually over a long distance, to a receiver that converts the signal back to a voltage. A simple receiver would consist of a resistor that would convert this current back to a voltage simply by Ohm's Law. A typical value for this resistor is 250ohm, resulting in a final voltage of 1-5V.

## Why Use Current Transmitters?

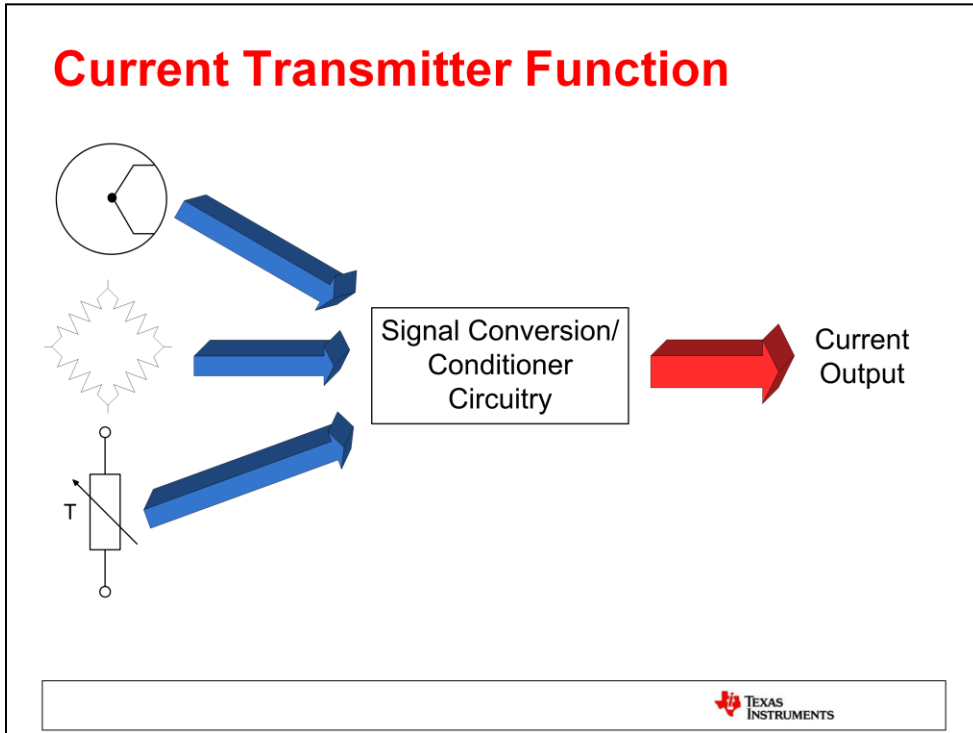
- Immunity to noise
  - Multiple unknown noise sources can exist between transmitter and receiver
  - Low impedance system prevents noise from impacting the accurate regulation of loop current
- Long distance transmission
  - Signals must often travel distances  $> 1$  mile
  - Impedance of long wires would severely attenuate a voltage signal
  - 4-20mA current loops are lossless, even over long distances
    - Kirchoff's Current Law states that the current in a loop is equal at any point within the loop



1) With respect to electronics, the industrial environment is very harsh. Signal transmissions occur on a factory floor or between buildings, and multiple unknown noise sources can be present at any given time. Thankfully, the inherent low impedance of a current loop system makes it much less sensitive to induced noise than, for example, the high impedance input of a voltage amplifier. Typical noise sources are on the order of  $\mu\text{A}$ , which is insignificant when compared to the 16mA signal span. Furthermore, using 4mA as a “live zero” improves signal-to-noise ratio at low levels, which allows low signal levels to be accurately interpreted without added noise or interference.

2) Sense and control signals must often travel distances of a mile or more. If a voltage transmission was sent over a mile-long wire, the impedance of the wire would cause enough attenuation to render the arriving signal unusable. 4-20mA current loops are essentially lossless, even at long distance, since the voltage drop caused by the long transmission wires does not impact the accuracy of the signal. Kirchoff's Current Law states the current in a loop is equivalent at any point in the loop, so if a current of 8mA is read at a receiver, the current at the transmitter a mile away must also equal 8mA

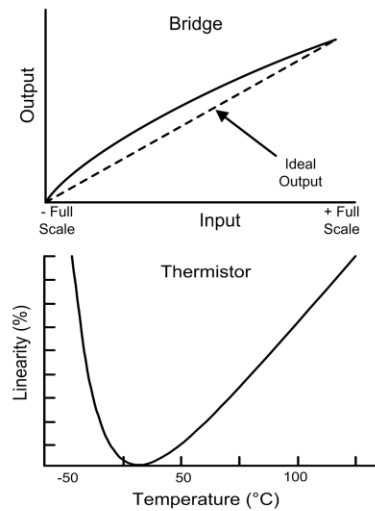
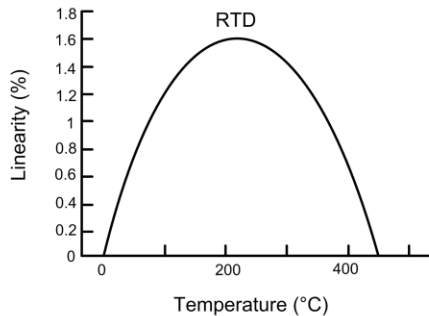
## Current Transmitter Function



Let's now look a little more closely at the function our XTR current transmitter parts perform. Transmitters are frequently used to send a proportional signal generated from a sensor measuring a real-world parameter, to a receiver which is typically located at a distant location. Our XTR current transmitters allow us to perform this task, as well as condition the signal depending upon the sensor's inherent properties.

## Why Is Signal Conditioning Required?

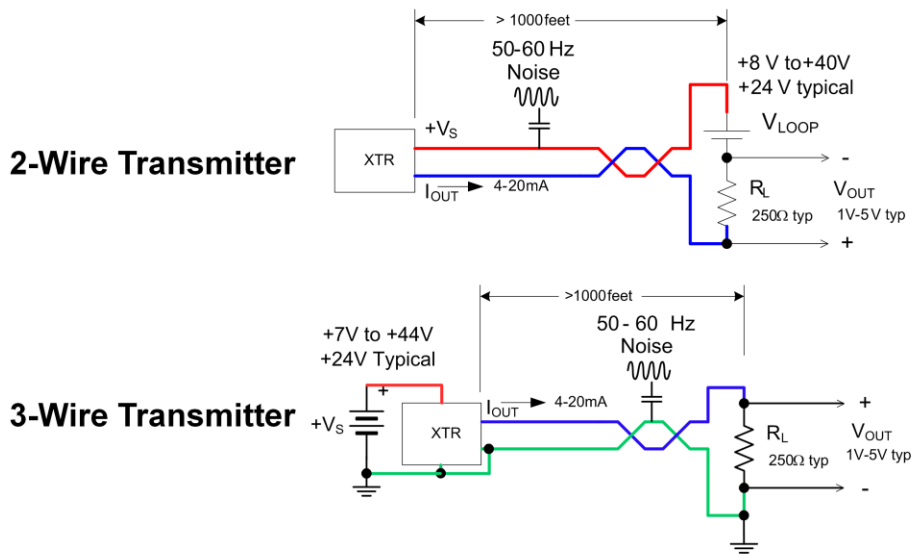
- Linearity errors on most sensors creates an unacceptable error.



TEXAS  
INSTRUMENTS

By inherent properties, I mean the typical non-linear response that is common among analog sensors. Shown here are some typical non-linear representations of a few commonly used sensors. The RTD (resistive thermal device) and thermistor curves have been normalized to better show the non-ideal component in their response. The non-linear response in the bridge figure can be seen by the positive bow and deviation from the ideal output. Without correction, this non-linear portion of the sensor's response feeds through to the output resulting in unwanted error. Many of our transmitters have specialized functionality intended to correct the non-linear aspect of a sensor's response.

## Transmitter Type Diagrams



TEXAS  
INSTRUMENTS

At this point we take a look at the basic diagrams of our transmitters. The two most common types of transmitters are the 2- and 3-wire types. As mentioned previously, an advantage of the current transmission line is immunity to noise, such as 50/60Hz power supply noise, that would otherwise couple into the long transmission lines.

One point to make here is that the name of a 2- or 3-wire transmitter does not refer to the number of wires that are used to connect the transmitter to the receiver. In both figures, there are only two wires that connect the two sections. The key difference between the transmitters is what signals that are present on those lines. The signals on the two-wire lines are supply (shown in red) and data (shown in blue). The signals on the 3-wire lines are data (shown in blue) and ground (shown in green). The additional third line (shown in red) of the three-wire transmitter is the power supply line.



## 2-Wire vs. 3-Wire Transmitter

- Application-specific parameters determine which transmitter type should be used
  - Accessibility and location
  - System power requirements
  - Sensor input or voltage/current input

Now we will look into what differentiates a 2-wire and a 3-wire transmitter. The choice of which type to use in a particular application depends on several factors, including location of the sensor and system power requirements.

## 2-Wire vs. 3-Wire Transmitter

- 2-Wire Transmitter (Loop powered)
  - Transmitter and sensor remotely located
  - Local power supply not practical
  - Input circuitry floats with respect to loop supply ground
- 3-Wire Transmitter (Locally powered)
  - Transmitter located close to power supply
  - Input is referenced to power supply ground
  - Also known as a voltage-to-current converter



A 2-wire transmitter is referred to as being loop powered. It does not derive its power from a local power supply, but rather from a supply that is located some distance away. Located close to the sensor, the transmitter and sensor can both be placed in remote locations in conditions that are unsuitable for a power supply. These types of applications typically involve simply measuring a parameter and transmitting the data. They often perform no other task than just data capture and reporting.

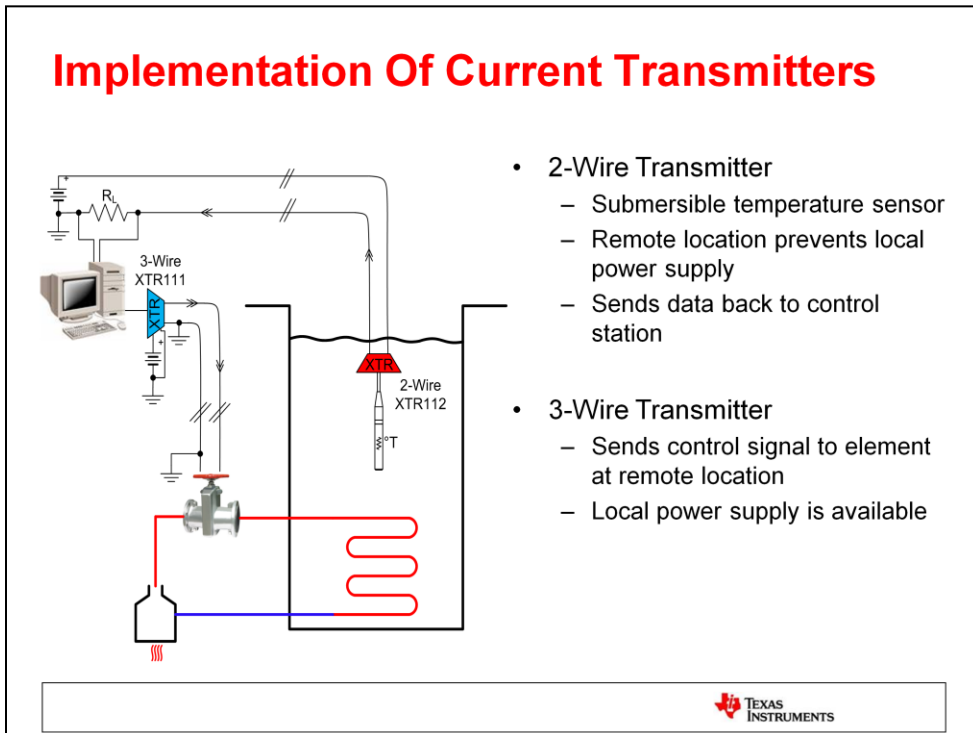
A 3-wire transmitter can be referred to as locally-powered or self-powered. The transmitter is commonly located at the available power supply and sends information out to a remote location. 3-wire transmitters more commonly send a command for a remote device to perform some action. The transmission consists of the signal and the return line. Power is not sent in the transmission line with the 3-wire transmitter.

## Common 2-Wire Transmitter Applications



Several common applications using two-wire transmitters can be seen here. They include temperature, pressure, and flow sensors. Two of the figures shown on the bottom right are submersible sensors which are placed under water for temperature and pressure measurement. Looking at these two, it is clear that accessibility is a significant issue given the environments where some of these sensors are utilized.

## Implementation Of Current Transmitters



To get a better idea on how the two types can be integrated into an application we look back to our previous diagram.

The goal here is to keep a remotely located liquid storage tank within a certain temperature range. As the liquid's temperature must be measured below the surface, a submersible temperature sensor is required. This severely limits the possibility of providing an on-board power supply to power the sensor. Due to the remote location, supply availability and type of data to be transmitted, a 2-wire approach is chosen. Two wires are used to connect the central monitoring station to the temperature sensor in the remotely located storage tank. Those two wires provide power and the return signal containing the proportional current based on the sensor's reading. The current is converted to a voltage when it passes through a load resistor, and the resulting voltage then is read by the monitoring station.

This creates a current loop that develops a voltage across the load resistor that varies as the temperature sensor responds to the temperature in the liquid. Once the monitoring station receives the data from the remote location, it can then decide what it wants to do with that data. In this example, if the temperature of the liquid becomes too low, a 3-wire transmitter can send a command for a valve can open up a line, allowing water that is heated in an external heating chamber to flow through coils placed inside the liquid storage tank. The valve does not require power to be sent from the monitor station

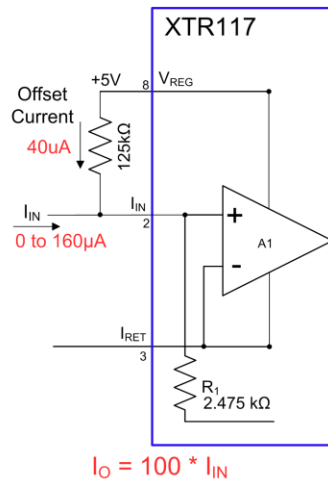
because it can have its own local power supply. The transmission to the valve consists of the current signal and a ground reference to tie to the valve's local ground to the monitoring station's ground. The three wires that give this type of transmitter its name are its dedicated supply and ground along with the current signal.

## 2-Wire Transmitters

Now that we have gone through an example on how 2- and 3-wire transmitters are implemented, let's take a closer look at how we actually interface with a two-wire transmitter.

## 2-Wire Typical Input Scaling

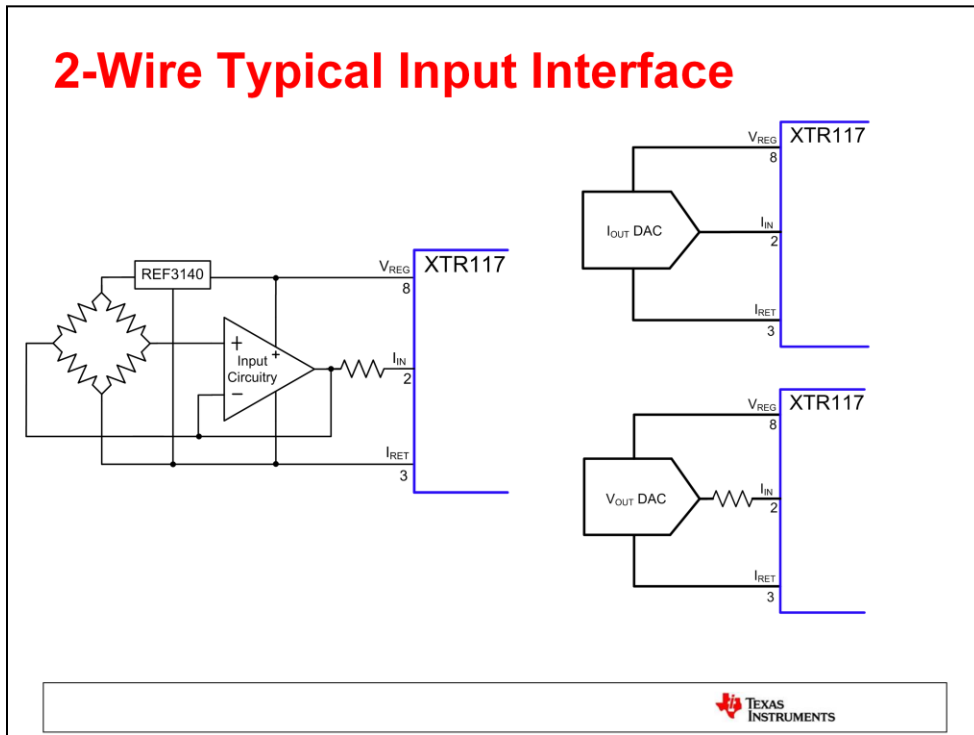
- 4-20mA span is 16mA
- XTR117 has current gain of 100
  - Input span is 160 $\mu$ A
- Offset current needed if input signal reaches zero



Here we see the input side of the 2-wire current transmitter XTR117. This device generates a current output proportional the current received at its input.

This device has a current gain of 100, so to generate a 4-20mA output signal, we must input a 40-200 $\mu$ A signal. The XTR117 allows quite a bit of flexibility in the design of the input circuitry stage. Some applications require under scale monitoring capability. This allows for the detection of unintended out of range operation of the sensor. By allowing a configurable low end set point, a user-defined under scale point can be set. Here I am showing how to set a 40 $\mu$ A offset to allow for a 4mA output current based on an zero input signal. The total input current fed into the device at a zero input condition is the 40 $\mu$ A offset which is amplified by 100 to yield a 4mA output. Likewise, with a full scale input condition of 160 $\mu$ A along with the 40 $\mu$ A offset current, the total input current of 200 $\mu$ A creates a 20mA signal at the output.

## 2-Wire Typical Input Interface



There are several ways to interface with the XTR117. Several are shown here, including a sensor signal being conditioned and then sent to the XTR117, as well as an input signal sent from a voltage or current DAC. An important thing to note here is that the input circuitry is all powered by the on-board regulator of the XTR117. In addition to being powered by the regulator, all of the returns are tied together at IRET. There is no true “ground” reference point for this circuitry, rather, it is referenced to the potential of IRET. I will explain in a few slides why this is so critical to a 2-wire system.

The input circuitry can be chosen to perform any required conditioning functionality needed, but current consumption must always be considered. The input circuitry must be chosen to keep the current consumed as low as possible. Being loop powered, all of the currents must return to the IRET pin. This means that the lowest possible output current the XTR117 is capable of transmitting is equal to the total current consumed by both the XTR117 itself as well as the input circuitry.

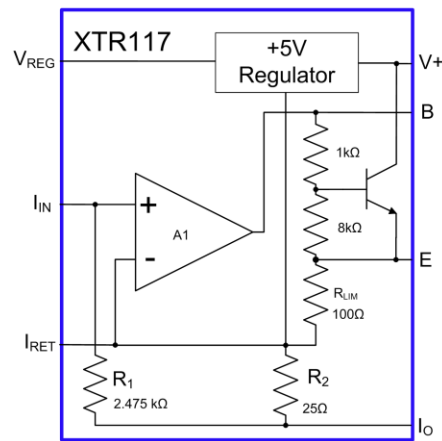
The XTR117 requires approximately 200uA of current to operate. Therefore, if an under scale current of 3.6mA was desired, that would leave a total current budget of 3.4mA to power all of the input circuitry while still being able to output a 3.6mA minimum output current. If more current than this was consumed by the



input circuitry and XTR117, such as 5mA for example, the lowest output current the XTR117 could output would be 5mA. This means that the circuit would not respond to inputs which result in output currents lower than 5mA.

## Typical 2-Wire Transmitter

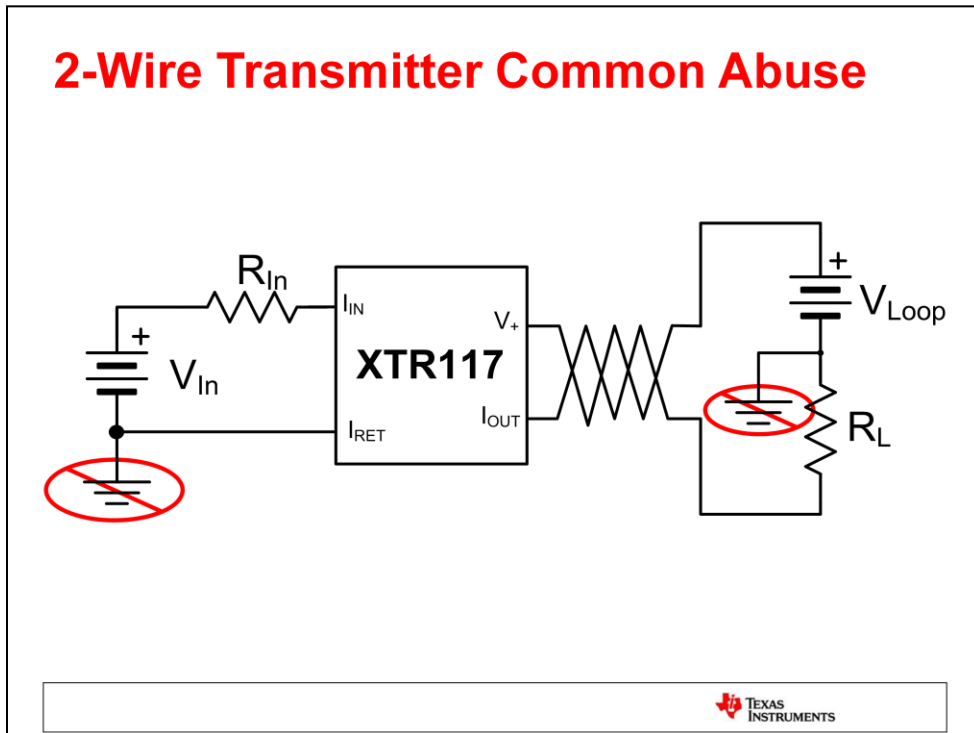
- $I_{RET}$  is not GND
- Current Input
- Current Output
- Current gain set by  $R_1$  and  $R_2$
- Regulator and input circuitry floats at  $I_{RET}$  potential



To further break down the differences in how these 2 and 3-wire transmitters are different, we need to look into how the 2-wire internal circuitry operates. To highlight one of the main aspects of the two-wire transmitter, the  $I_{RET}$  pin is not GND. We will soon see why this is such an important condition for the proper operation of this device.

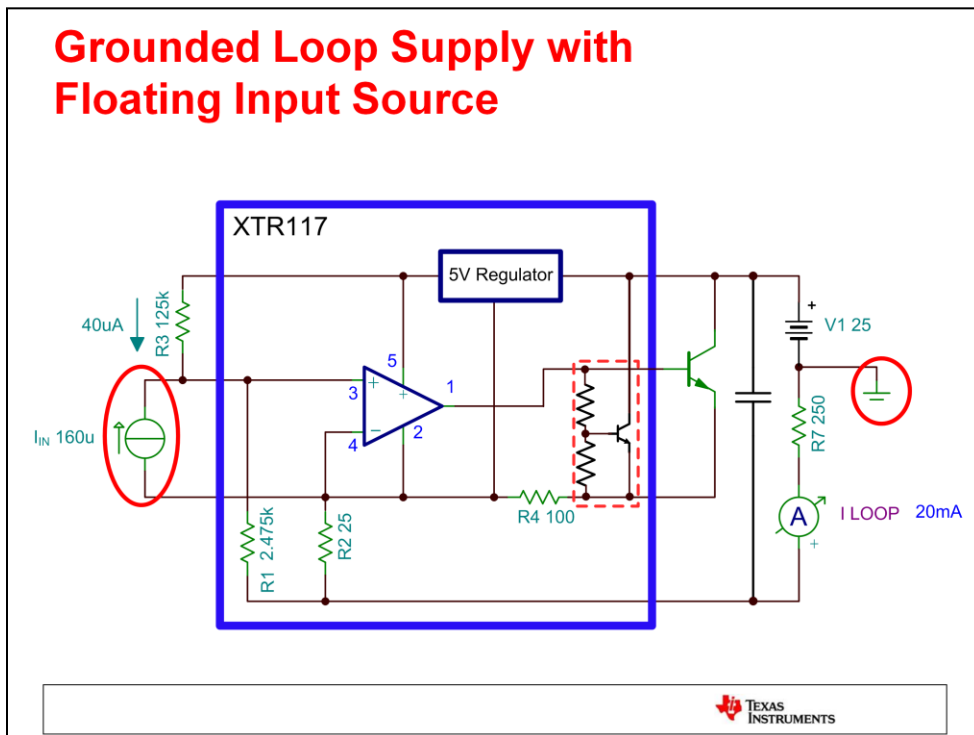
Another important characteristic is that this is a current input/current output device that has a current gain set by the internal resistors  $R_1$  and  $R_2$ .

## 2-Wire Transmitter Common Abuse



In starting to look into the operation of the circuit, I'll first show this diagram. This XTR117 circuit can not operate correctly because the input is referenced to the same potential as the loop supply which violates the predefined operating conditions of the XTR117. The input circuitry and IRET must be allowed to float with respect to the loop supply ground. With IRET pin pulled to ground, the IRET pin can not float to the necessary voltage required to allow for the circuit to work properly.

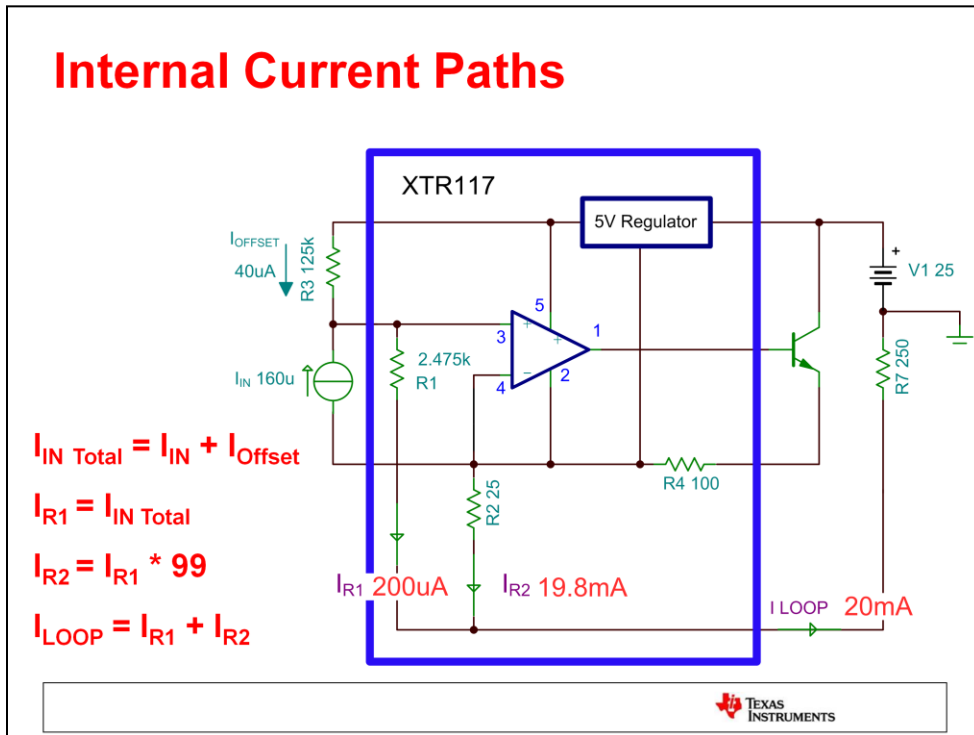
## Grounded Loop Supply with Floating Input Source



This is a simplified internal drawing of the XTR117. This circuit will allow us to see how the device operates and why it has the requirement of a floating input stage. One point to note about this circuit is the internal transistor section outlined in red - this section of the circuit is bypassed entirely when an external transistor is present so the internal transistor will be removed from further diagrams.

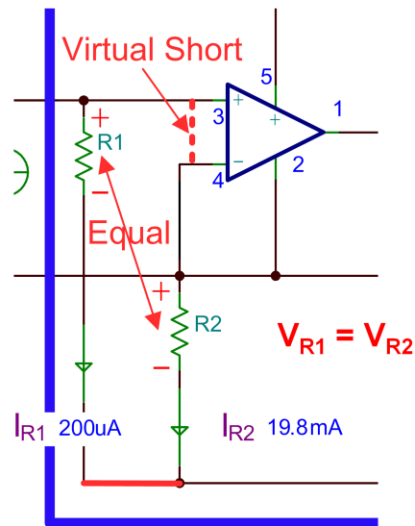
In this circuit we can see that the input circuitry, shown here as a current source, is floating with respect to the loop supply ground. The current source is tied to IRET as its reference. We can see that there is a total of 200uA, comprised of 160uA input signal and a 40uA offset current from the internal regulator, that flows into the input of the device yielding an output current of 20mA.

## Internal Current Paths



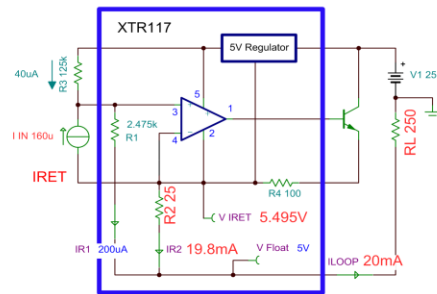
Looking closer in how we achieve the current gain of 100, we see that there are two current paths feeding the I loop current of 20mA. Because of the high input impedance of the internal amplifier, all of the current provided at the input of the device flows through R1. This develops a voltage in this case equal to 495mV. Due to the amplifier configuration, this same amount of voltage appears across R2. The value of R2 is 99 times less than the value of R1 yielding a current flowing through R2 to be 99 times the current flowing through R1. The total of these two currents adds up to arrive at 100 times the input current resulting in the 20mA output based on the 200uA input.

## Equal Path Voltages Created



I mentioned that the voltage across R1 also appears across R2. This may not be intuitively obvious so here we take a closer look at this section of the circuit. The top of resistor R1 and R2 are connected together through the virtual short of the amplifier. The bottom of the resistors are connected at the out line. The equal voltages in the parallel paths allow for the current to be scaled as needed.

## Calculating I<sub>RET</sub> Level

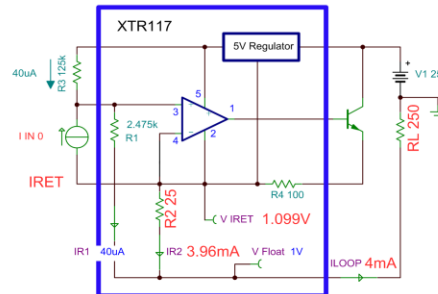


$$V_{\text{FLOAT}} = I_{\text{LOOP}} * R_L$$

$$V_{R2} = R_2 * I_{R2}$$

$$V_{\text{IRET}} = V_{\text{FLOAT}} + V_{R2}$$

$$V_{\text{IRET}} = 5.495\text{V}$$



$$V_{\text{FLOAT}} = I_{\text{LOOP}} * R_L$$

$$V_{R2} = R_2 * I_{R2}$$

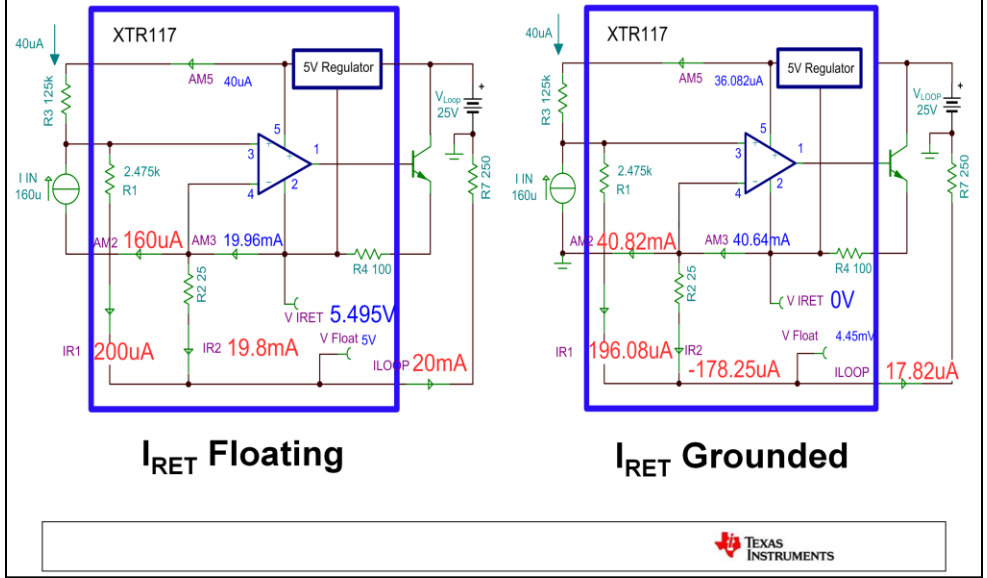
$$V_{\text{IRET}} = V_{\text{FLOAT}} + V_{R2}$$

$$V_{\text{IRET}} = 1.099\text{V}$$

Why is it important to know what the current flowing through R2 is? To learn why the IRET pin can not be tied to ground we need to first determine what the voltage IRET reaches if left to float. The voltage level of IRET is calculated by the voltage created by the loop current flowing through the load resistor as well as the internal current flowing through R2. With a maximum-scale input of 160uA, for example, the voltage level of IRET is 5.495V.

On the right, looking at the same circuit but at minimum-scale of operation, we can see that the voltage level of IRET has significantly changed. A total input current of 40uA creates a 4mA output current level setting the IRET voltage to 1.099V. Having seen how the circuit operates and how the IRET voltage level moves depending upon the input/output current levels and load value, we can see why the IRET can not be tied to ground.

## Effects of Grounding $I_{RET}$



By comparing the operating circuit on the left with the same circuit but with a grounded  $I_{RET}$  pin, we can get a better idea as to what is the limiting factor of the circuit. What was previously a high impedance node of the current source, which forced the current to flow through the 25 ohm resistor to the output, now appears as a low impedance short for the transistor with the internal 100 ohm resistor limiting the short-circuit current to approximately 41 mA. With the  $I_{RET}$  pin grounded current is unable to flow through R2 in the correct direction to allow for the circuit to operate correctly.

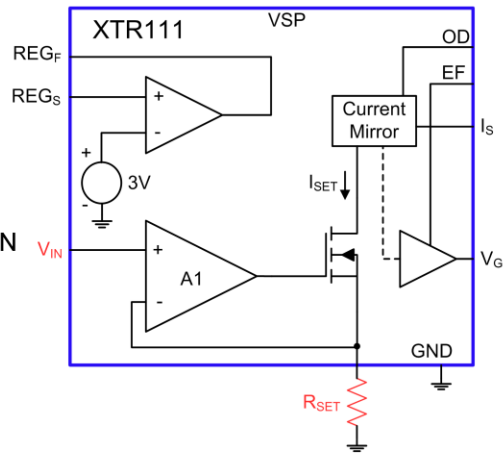


## 3-Wire Transmitters

We have discussed the internal operation of a 2-wire transmitter. Let's look at the 3-wire transmitters now so we can see how to interface with signals that are referenced to ground.

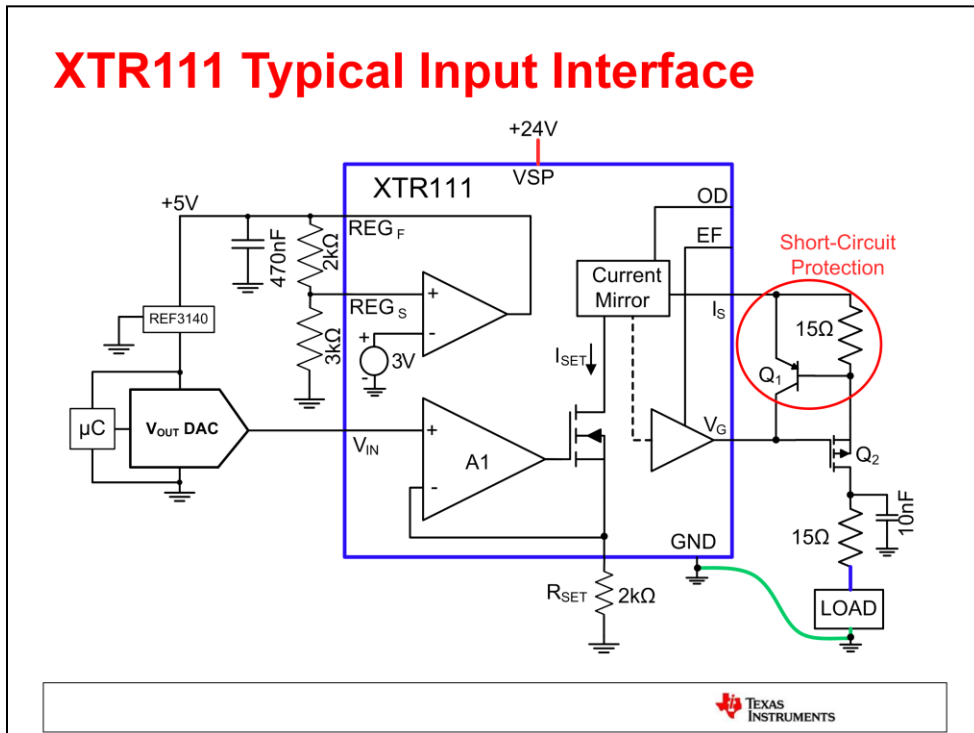
## Typical 3-Wire Transmitter

- Input and Output are referenced to GND
- Voltage Input
- Current Output
- Current gain set by  $V_{IN}$  and  $R_{SET}$
- Regulator referenced to GND



In contrast to the XTR117, the XTR111 has ground referenced on-board adjustable regulator that can be used to power external input circuitry. The regulator, though, does not necessarily *need* to be used to power the input circuitry since all voltages are referenced to the same GND. The current gain for this device is set with external components making it configurable to a variety of application requirements.

## XTR111 Typical Input Interface




This circuit shows the typical configuration for interfacing to the XTR111. The on-board regulator here is configured to a 5V output that is then fed to an external reference that powers the ground referenced microcontroller and DAC. A ground referenced bridge sensor could be used as an input source similarly to the DAC shown here. Another difference between the two and three wire transmitters is in their output's current dependency on the current consumed in the input circuitry. The loop powered transmitter required all of current consumed by the input circuitry and transmitter to be referenced to I<sub>RET</sub> requiring low power devices to allow for low level current outputs. The three wire transmitter is locally powered and the output is not dependent on how much current is consumed in the input circuit.

This circuit operates very differently than the two-wire circuitry that we previously looked at. Here we develop an I<sub>SET</sub> current based on the voltage at the input divided by R<sub>SET</sub>. A current mirror provides a gain of 10 which is transferred to the load through the output FET. The additional Q<sub>1</sub> and 15ohm resistor shown in the top right provide short-circuit protection, and the 15ohm resistor and 10nF capacitor provide filtering of the output current before being sent to the load. The two transmission wires that would be used can be seen in the output of the 15ohm filter resistor and the ground line that connects the load's ground to the XTR111's ground. The third wire of the three-wire current transmitter is the

supply line connecting the device to the local 24V supply.

## 4-20mA Product Family

2-Wire General Purpose	XTR101	I_IN to I_OUT Converter, Current Excitation
	XTR115	I_IN to I_OUT Converter, 5V Regulator, 2.5V Reference
	XTR116	I_IN to I_OUT Converter, 5V Regulator, 4.096V Reference
	XTR117	I_IN to I_OUT Converter, 5V Regulator
2-Wire RTD Conditioner	XTR105	RTD Conditioner, 800uA Current Sources
	XTR108	RTD Conditioner, Digital Calibration, Input Mux
	XTR112	RTD Conditioner, 250uA Current Sources
	XTR114	RTD Conditioner, 100uA Current Sources
2-Wire Bridge Conditioner	XTR106	Bridge Conditioner, Linearization Correction
3-Wire General Purpose	XTR110	Selectable Input/Output Ranges, Voltage to Current Converter
	XTR111	Configurable Input/Output Ranges, Voltage to Current Converter
	XTR300	Configurable Input/Output Ranges, Current/Voltage Output Mode
4-20mA Receiver	RCV420	4-20mA input, 0-5V Output
		

To sum up, when looking into transmitting data through noisy environments a current transmitter is very robust tool to ensure data integrity. The choice of which transmitter type to use mainly depends upon the source of your signal and how accessible it is to provide power there.

We have general purpose two-wire transmitters like the XTR117 that we looked at earlier along with specialized RTD and bridge conditioners. We also have general purpose three-wire transmitters like the XTR111 that are easily configured to operate in several input/output ranges. We also have a 4-20mA receiver in the RCV420. This device converts a 4-20mA signal and level shifts it to a 0-5V output.

# Thank You!