Debugging CAN, LIN, and FlexRay Automotive Buses with an Oscilloscope

APPLICATION NOTE

Tektronix®

Introduction

Embedded systems applications growing rapidly in the automotive industry. Many vehicle designs use CAN, LIN or FlexRay to communicate among electronic control units (ECUs), and between ECUs and sensors, actuators and displays. These buses are critical in providing real-time communications in and among important subsystems from braking systems to infotainment systems.

CAN, LIN, and FlexRay are relatively mature bus protocols and are designed to be robust and easy to integrate. Even so, communications can be impacted by noise, board layout, and power-up/down timing. Problems can include excessive bus errors and lock-ups. Unlike basic protocol analyzers, oscilloscopes equipped with protocol decoding, can be used to see both the decoded bus traffic, as well as signal quality. This ability to see bus signals and decoded traffic makes oscilloscopes the best choice for troubleshooting.

Perhaps more importantly, oscilloscopes can be used to troubleshoot problems at the system level. Automobiles rely on extensive networks of sensors, actuators and displays, and many problems involve bus timing relative to I/O events or values. Oscilloscopes are well-suited for looking at I/O signals and bus transactions at the same instant. Because of this capability, they are the instrument of choice for system-level debugging.

THIS APPLICATION NOTE

- Gives a brief orientation on the physical layer and packet structures of CAN, LIN, and FlexRay buses, with a goal of providing just enough detail to help with troubleshooting
- Explains how to set up decoding on an oscilloscope equipped with CAN, LIN or FlexRay decoding
- Explains how to interpret decoded serial bus data on an appropriately-equipped oscilloscope
- Explains what triggering and searching options are available

With optional serial triggering and analysis capability, Tektronix oscilloscopes become powerful tools for embedded system designers working with CAN, LIN, and FlexRay buses. In this application note the 5 Series MSO is used to demonstrate decoding and triggering on these buses.

[1] Support for serial bus standards vary depending on the oscilloscope model. For a table of buses supported by different Tektronix oscilloscopes, please see Appendix A or visit www.tektronix.com.

CAN/CAN FD

The Controller Area Network (CAN) was originally developed in the 1980s by the Robert Bosch GmbH as a low cost communications bus between devices in electrically noisy environments. Mercedes-Benz became the first automobile manufacturer in 1992 to employ CAN in their automotive systems. Today, every automotive manufacturer uses CAN controllers and networks to control a variety of Electronic Control Units (ECUs) in their automobiles. It is the primary bus used for engine timing controls, anti-lock braking systems and power train controls to name a few. And due to its electrical noise tolerance, minimal wiring, excellent error detection capabilities and high data transfer speeds, CAN is expanding into other applications such as industrial control, marine, medical, aerospace, and more.

As vehicle networks have evolved to support many more functions, an urgent need has arisen to support faster data communication between nodes. This has led to CAN FD, a higher speed version of CAN which can achieve a max data rate of 8 Mbps with a payload up to 64 bytes long compared to the max data rate of 1 Mbps and payload of 8 bytes for CAN. The first version of the CAN FD standard was released in 2012 but it was later updated into an ISO standard called ISO CAN FD in 2015. The ISO version introduced additional safeguards to improve communication reliability. The original version is now known as non-ISO CAN FD and is not compatible with ISO CAN FD.

HOW IT WORKS

The CAN/CAN FD bus is a balanced (differential) 2-wire interface running over a Shielded Twisted Pair (STP), Un- shielded Twisted Pair (UTP), or ribbon cable. Each node uses a male 9-pin D connector. . A number of different data rates are defined, with 1Mb/s being the fastest for CAN and 8 Mb/s the fastest for CAN FD. All modules must support at least 20 kb/s. Normally all devices in a system transfer information at uniform and fixed bit rates. Maximum cable length depends on the data rate used. The maximum line length can be thousands of meters at low speeds; 40 meters at 1 Mb/s is typical. Termination resistors are used at each end of the cable.

Non Return to Zero (NRZ) bit encoding is used with bit stuffing to ensure compact messages with a minimum number of transitions and high noise immunity. The CAN bus interface uses an asynchronous transmission scheme where any node may begin transmitting anytime the bus is free. Messages are broadcast to all nodes on the network. In cases where multiple nodes initiate messages at the same time, bitwise arbitration is used to determine which message is higher priority. Messages can be one of four types:

MESSAGE TYPES	DESCRIPTION	
Data Frame	Used to transmit data	Data and Remote frames are controlled by start and stop bits at the beginning and end of each frame and include the following fields: Arbitration field, Control field, Data field, CRC field and an ACK field.
Remote Transmission Request (RTR) Frame	Used to request data	
Error Frame	Any node on the bus that detects an error transmits an error frame which causes all nodes on the bus to view the current message as incomplete and the transmitting node to resend the message	
Overload Frame	Initiated by receiving devices to indicate they are not ready to receive data yet	

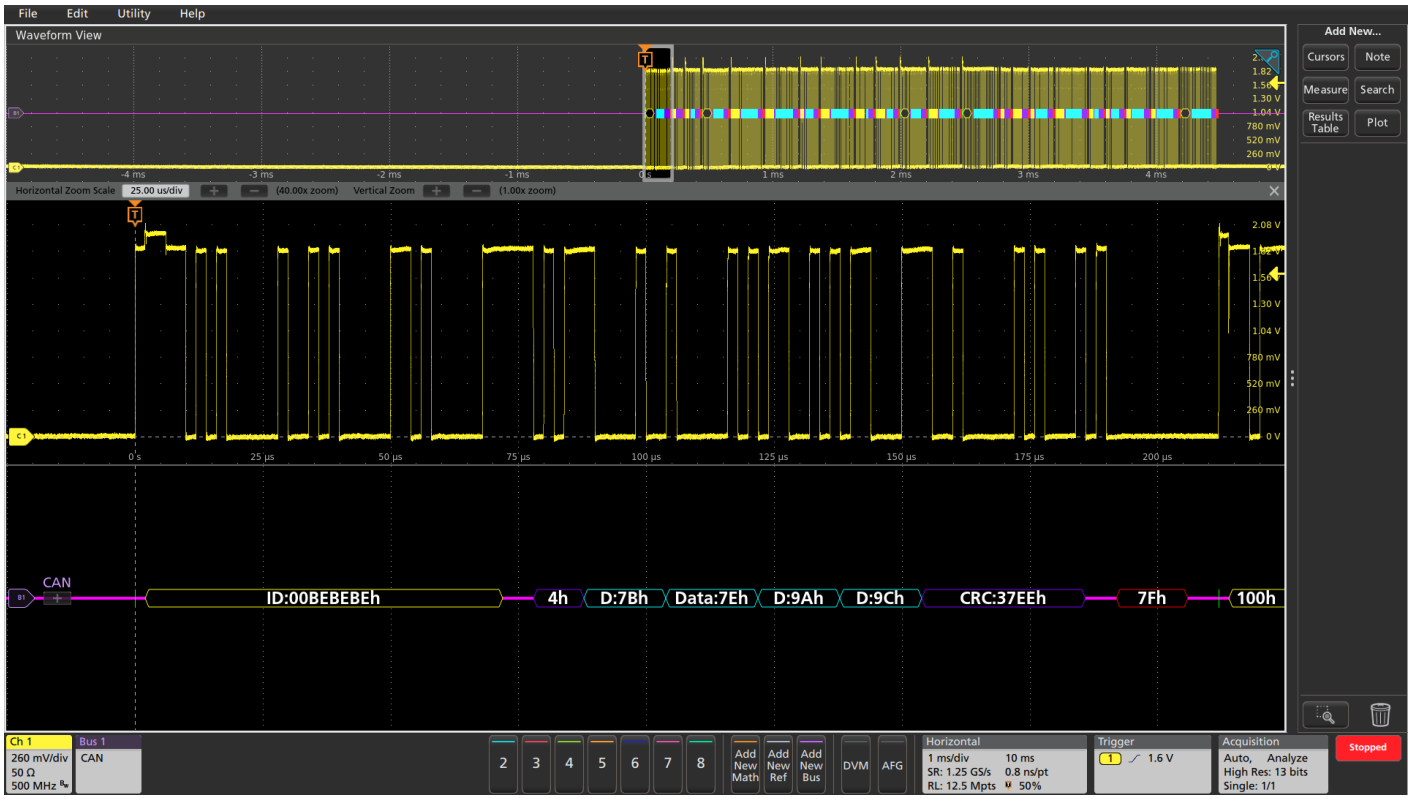
Structure of Data and Remote Transmission Request Frames

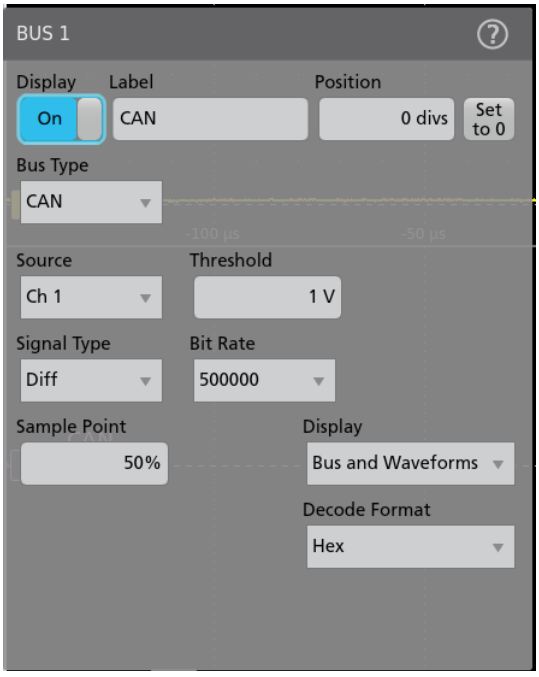
CAN 2.0	SOF 1 bit	Arbitration Field 11 bits (Std ID) 29 bits (Ext ID)	Control Field 6 bits	Data Field 0-8 bytes	CRC Field 16 bits	ACK 2 bits	EOF 7 bits	INT 3 bits
CAN FD	SOF 1 bit	Arbitration Field 12 bits (Std ID) 32 bits (Ext ID)	Control Field 8 or 9 bits	Data Field 0-64 bytes	CRC Field 18 or 22 bits	ACK 2 bits	EOF 7 bits	INT 3 bits

FIELD	DESCRIPTION
SOF	The frame begins with a start of frame (SOF) bit which is the same for CAN and CAN FD
Arbitration	Includes an Identifier (address) and the Remote Transmission Request (RTR) bit used to distinguish between a data frame and a data request frame, also called a remote frame. The identifier can either be standard format (11 bits - version 2.0A) or extended format (29 bits - version 2.0B). CAN FD shares the same addressing as CAN for standard and extended formats but removes the RTR bit and maintains a dominant r1 bit.
Control	Consists of six bits including the Identifier Extension (IDE) bit which distinguishes between a CAN 2.0A (11 bit identifier) standard frame and a CAN 2.0B (29 bit identifier) extended frame. The Control Field also includes the Data Length Code (DLC). The DLC is a four bit indication of the number of bytes in the data field of a Data frame or the number of bytes being requested by a Remote frame. CAN FD uses eight or nine bits in the Control Field and also uses the IDE, r0 and DLC bits. Three additional bits are added that include Extended Data Length (EDL) used to determine if packet is CAN or CAN FD, Bit Rate Switch (BRS) used to separate arbitration phase from data phase and Error State Indicator (ESI). The same four bit DLC is used differently in CAN FD for lengths ≥ 8.
Data	The CAN data field consists of 0 to 8 bytes of data. CAN FD supports 0 to 8 bytes but has an increased payload ability to support 12, 16, 20, 32, 48 or 64 bytes.
CRC	A 15 bit cyclic redundancy check code and a recessive delimiter bit is used in CAN. CAN FD uses 17 bits (plus CRC delimiter bit) for payloads ≤ 16 bytes or 21 bits (plus CRC delimiter bit) for ≥ 16 bytes. There are 4 additional stuff bits used for CAN FD.
ACK	The Acknowledge field is two bits long. The first is the slot bit, transmitted as recessive, but then overwritten by dominant bits transmitted from any node that successfully receives the transmitted message. The second bit is a recessive delimiter bit. There is a slight difference in CAN FD where the receiver recognizes 2 bit times as a valid ACK.
EOF	Seven recessive bits indicate the end of frame (EOF).

The intermission (INT) field of three recessive bits indicates the bus is free.

Bus Idle time may be any arbitrary length including zero.



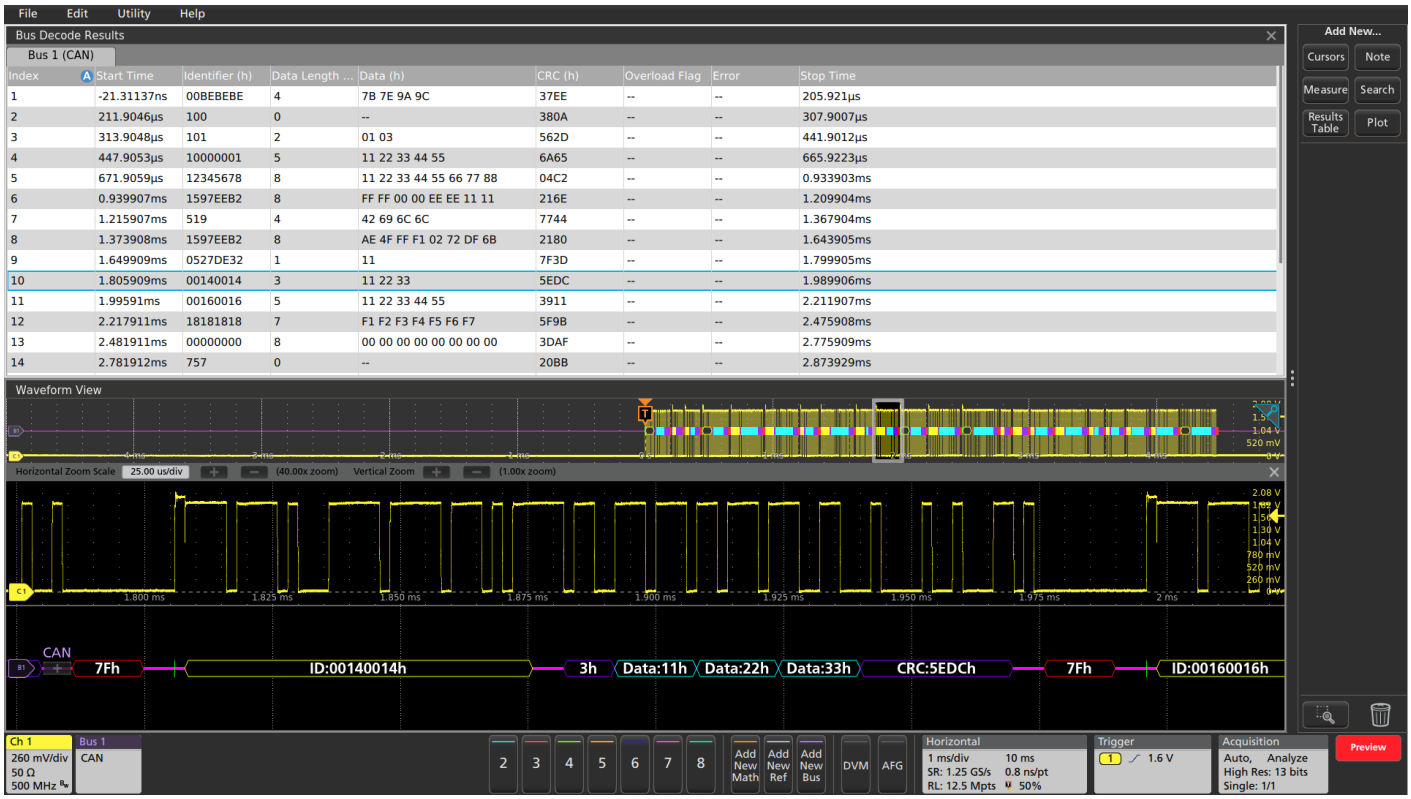


SETTING UP CAN BUS DECODING

On Tektronix oscilloscopes equipped with CAN decoding and triggering, pressing the front panel Bus button lets you define inputs to the scope as a bus. To enable the oscilloscope to decode information being transferred, you enter some basic parameters:

- Type of signal
- Input channel
- Bit rate
- Voltage threshold
- Sample point (as a percent of bit time)

The CAN bus is a differential signal. Although the oscilloscope can acquire and decode the bus using single-ended probing, the signal fidelity and noise immunity is improved by using differential probing.



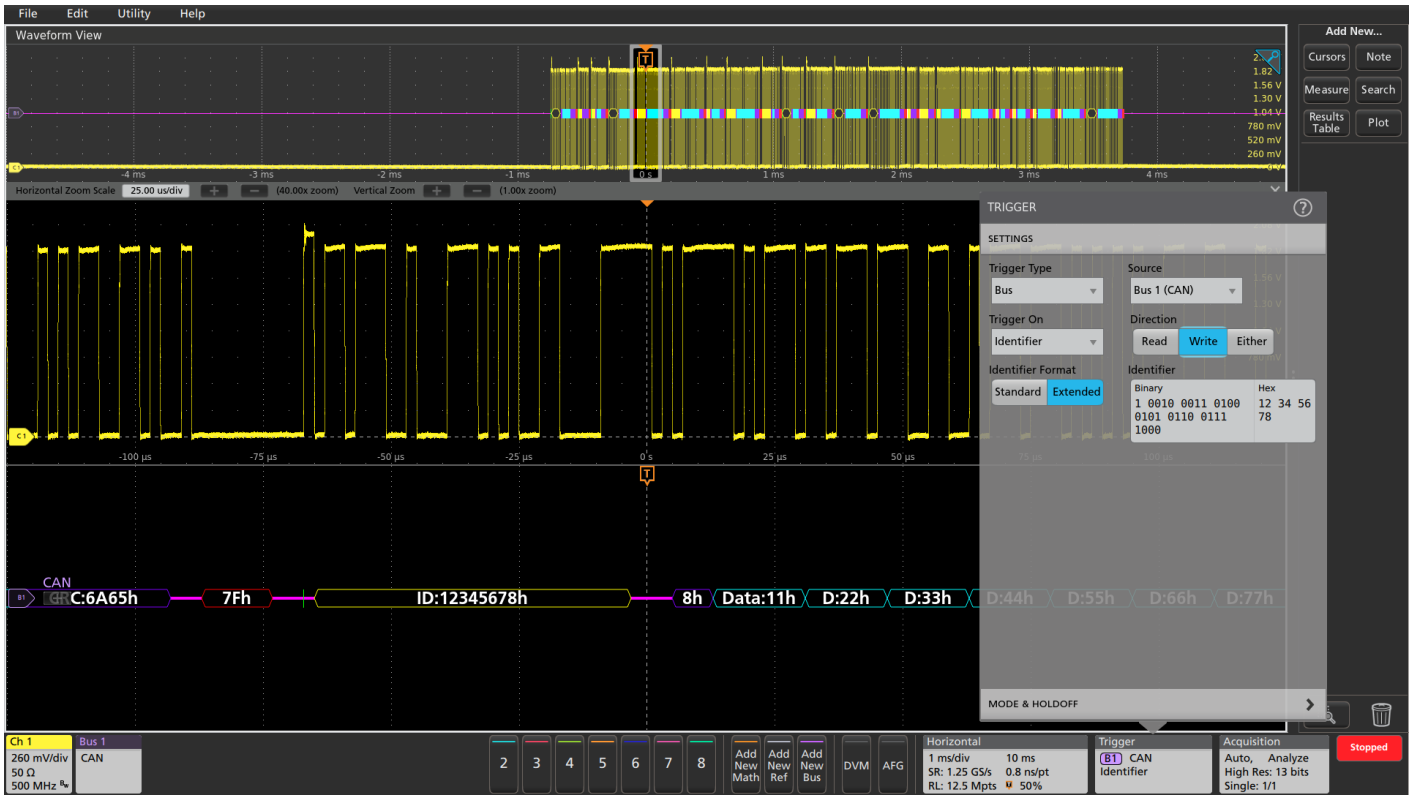
INTERPRETING CAN BUS INFORMATION

The decoded bus waveform indicates the elements of a CAN message using color-coded graphics.

For firmware engineers, the Results Table format may be more useful. This time-stamped display of bus activity can be easily compared to the software listings, and provides easy calculation of the execution speed.

The Results Table also provides linkage back to the waveform displays. You can tap a line in the tabular display and the oscilloscope automatically zooms in on the corresponding bus signals and resulting decoded bus waveform, shown in the lower section of the screen.

CAN BUS ELEMENT	INDICATED BY
Start of Frame is indicated by a vertical green bar.	
Data Length Control (DLC) is shown in a purple box. DLC values can be displayed in either hex or binary.	DLC:3h
Identifiers are shown in yellow boxes. Identifier values can be displayed in either hex or binary.	ID:00140014h
Data is shown in cyan boxes. Data values can be displayed in either hex or binary.	Data:112233h
CRC values are shown in purple boxes.	CRC:5EDCh
End Of Frame is indicated by a red box.	EOF:7Fh

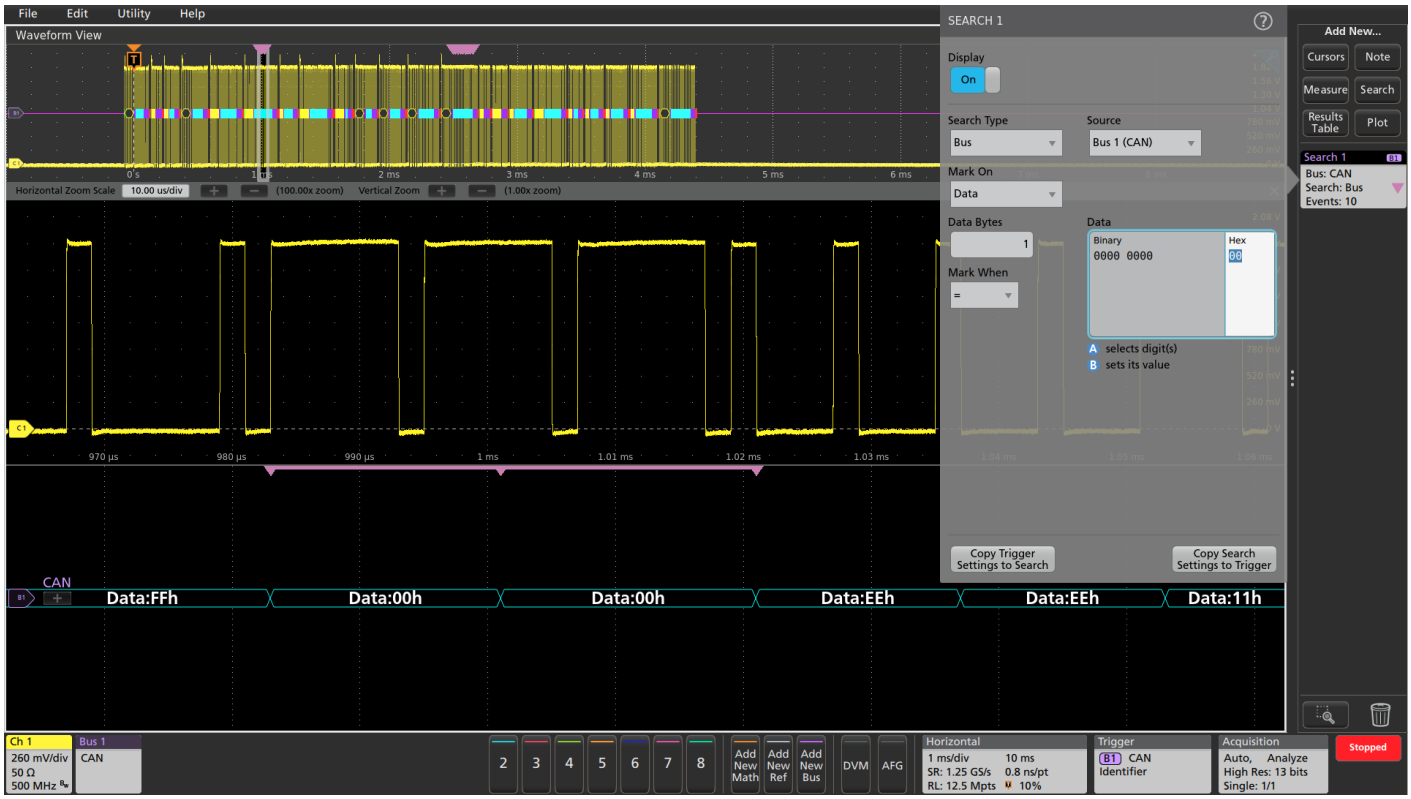


TRIGGERING ON CAN BUS ACTIVITY

Begin able to trigger an acquisition based on specific bus activity makes the oscilloscope an important tool in system-level debugging. When the bus trigger is correctly set up, the oscilloscope will capture all input signals synchronized to the specified bus activity. This example shows the oscilloscope triggering on a write to extended identifier 12345678 hex.

The full CAN bus triggering capabilities include the following trigger types.

TRIGGER ON	DESCRIPTION
Start of Frame	Trigger on any SOF field
Frame Type	Data Frame, Remote Frame, Error Frame, or Overload Frame
Identifier	Any specific 11 or 29 bit identifier values with Read / Write qualification
Data	Any user-specified CAN data
Missing Ack	Trigger anytime the receiving device does not provide an acknowledge
Bit Stuffing Error	Trigger if a bit stuffing error is detected
End of Frame	Trigger on any EOF field



SEARCHING FOR CAN BUS ACTIVITY

On a Tektronix oscilloscope equipped with CAN decoding, you can use the automated Wave Inspector search to find all of the bus events that meet specific search criteria and determine how many of them occurred during an acquisition. The setup is similar to bus trigger setup, with the same alternatives for specifying criteria. In this example the search function is set to automatically search for data values of 00 hex. It found and marked 10 occurrences.

LIN

The Local Interconnect Network (LIN) bus was developed by the LIN consortium in 1999 as a lower cost alternative to the CAN bus for applications where the cost, versatility, and speed of CAN were overkill. These applications typically include communications between intelligent sensors and actuators such as window controls, door locks, rain sensors, windshield wiper controls, and climate control, to name a few.

However, due to its electrical noise tolerance, error detection capabilities, and high speed data transfer, CAN is still used today for engine timing controls, anti-lock braking systems, power train controls and more.

HOW IT WORKS

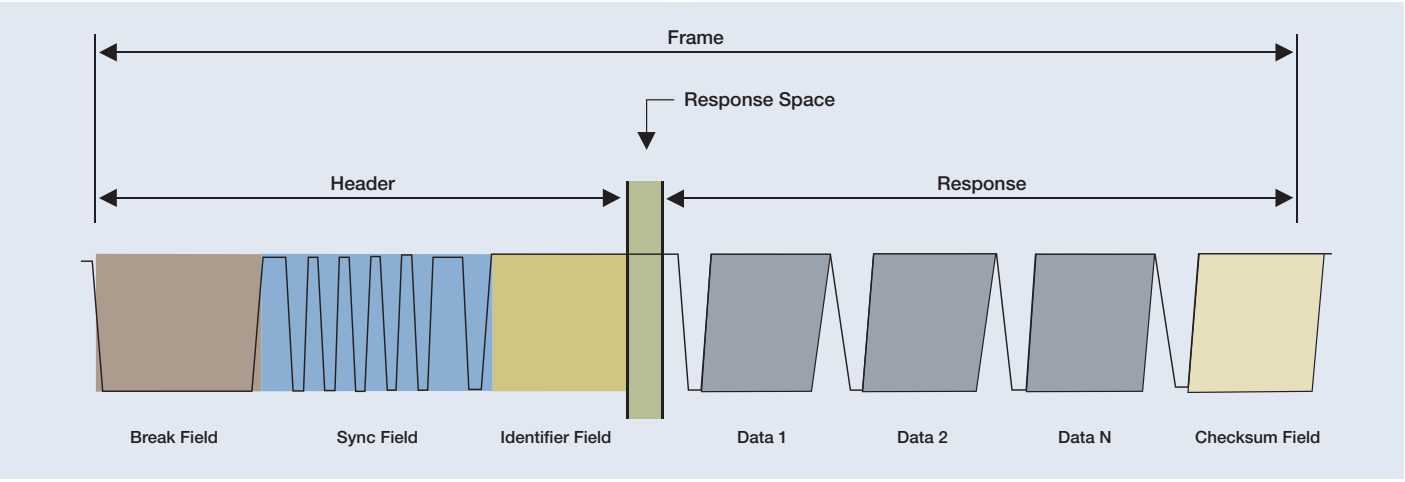
The LIN bus is a low-cost, single-wire implementation based on the Enhanced ISO9141 standard. LIN networks have a single master and one or more slaves. All messages are initiated by the master with only one slave responding to each message, so collision detection and arbitration capabilities are not needed as they are in CAN. Communication is based on UART/SCI with data being sent in eight-bit bytes along with a start bit, stop bit and no parity. Data rates range from 1 kb/s to 20 kb/s. While this may sound slow, it is suitable for the intended applications and minimizes EMI.

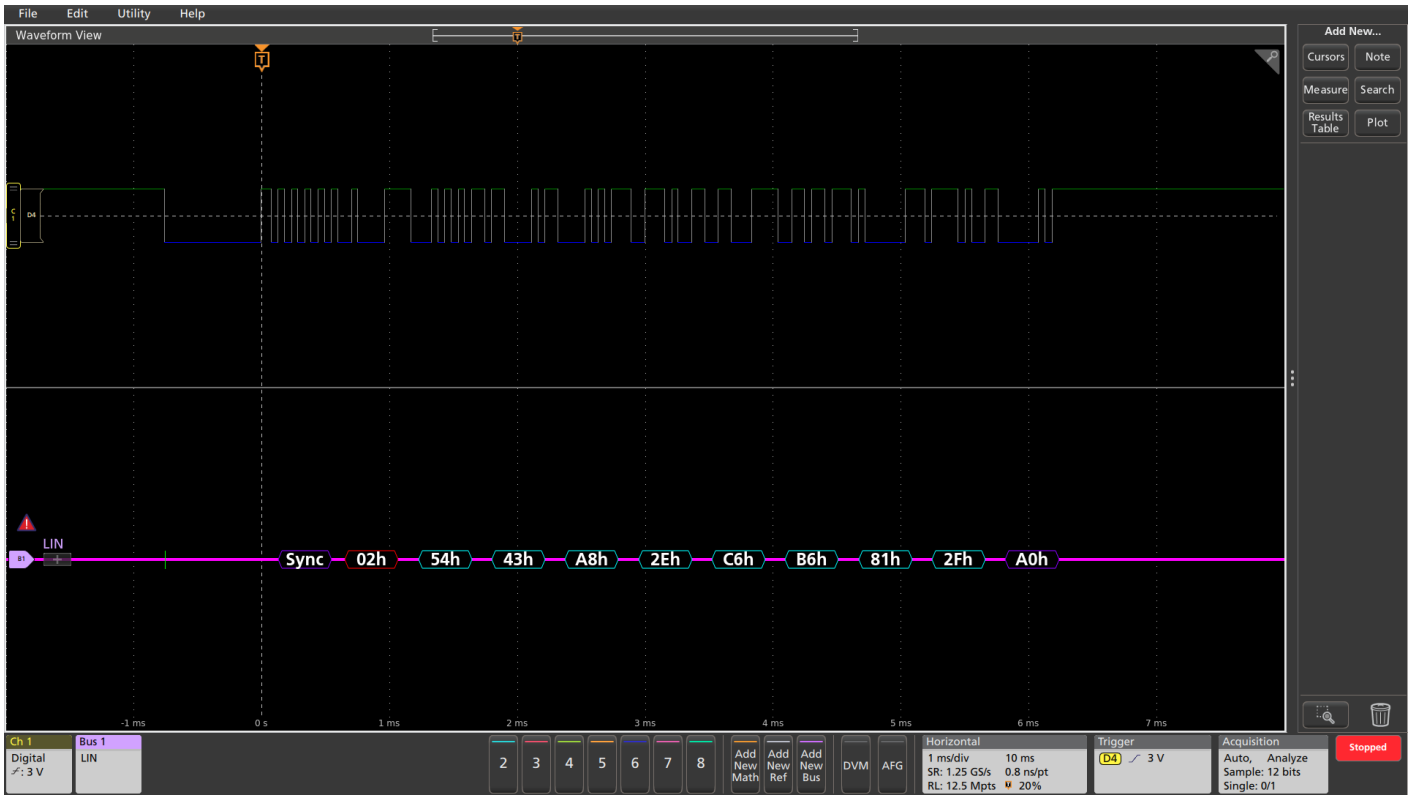
The LIN bus is always in one of two states: active or sleep. When it's active, all nodes on the bus are awake and listening for relevant bus commands. Nodes on the bus can be put to sleep by either the Master issuing a Sleep Frame or the bus going inactive for longer than a predetermined amount of time. The bus is then awakened by any node requesting a wakeup or by the master node issuing a break field.

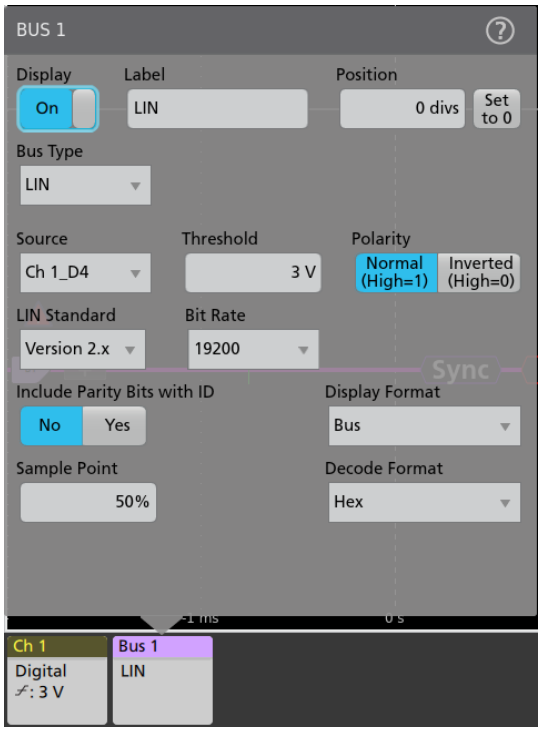
LIN frames consist of two main parts, the header and the response. The header is sent by the master while the response is sent by the slave. The header and response each have subcomponents:

HEADER COMPONENTS	DESCRIPTION
Break Field	Used to signal the beginning of a new frame. It activates and instructs all slave devices to listen to the remainder of the header
Sync Field	Used by the slave devices to determine the baud rate being used by the master node and synchronize themselves accordingly
Identifier Field	Specifies which slave device is to take action

RESPONSE COMPONENTS	DESCRIPTION
Data	The specified slave device responds with one to eight bytes of data
Checksum	Computed field used to detect errors in data transmission. The LIN standard has evolved through several versions that have used two different forms of checksums. Classic checksums are calculated only over the data bytes and are used in version 1.x LIN systems. Enhanced check- sums are calculated over the data bytes and the identifier field and are used in version 2.x LIN systems.





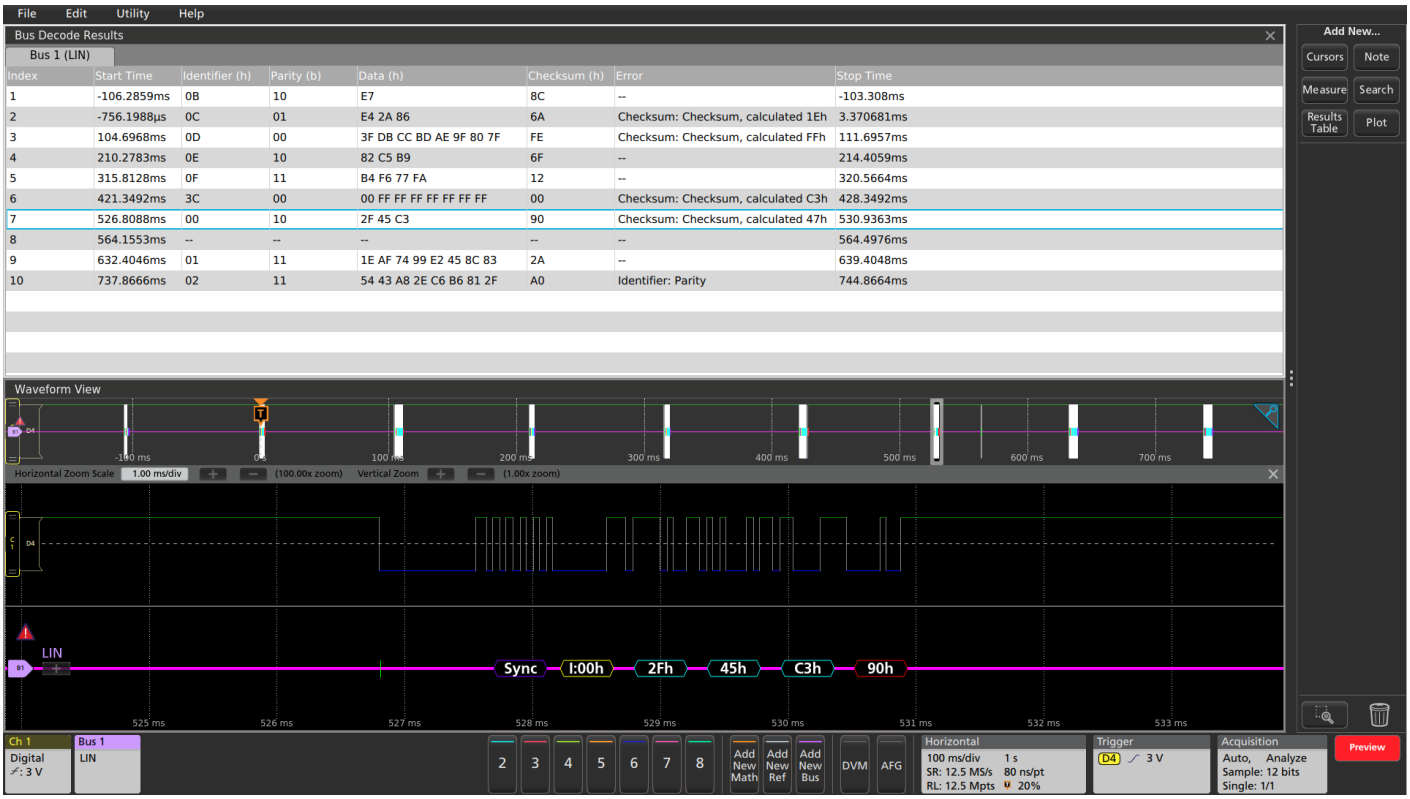


SETTING UP LIN BUS DECODING

On Tektronix oscilloscopes equipped with LIN decoding and triggering, pressing the front panel Bus button lets you to define inputs to the scope as a bus. To enable the oscilloscope to decode the information being transferred on the bus, you enter some basic parameters:

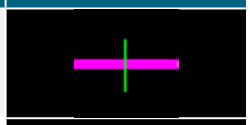
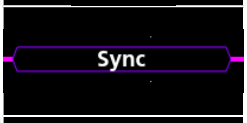
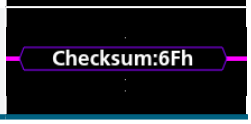
- Input channel
- LIN version being used
- Bit rate
- Polarity
- Threshold
- Where to sample the data (as a percent of bit time),

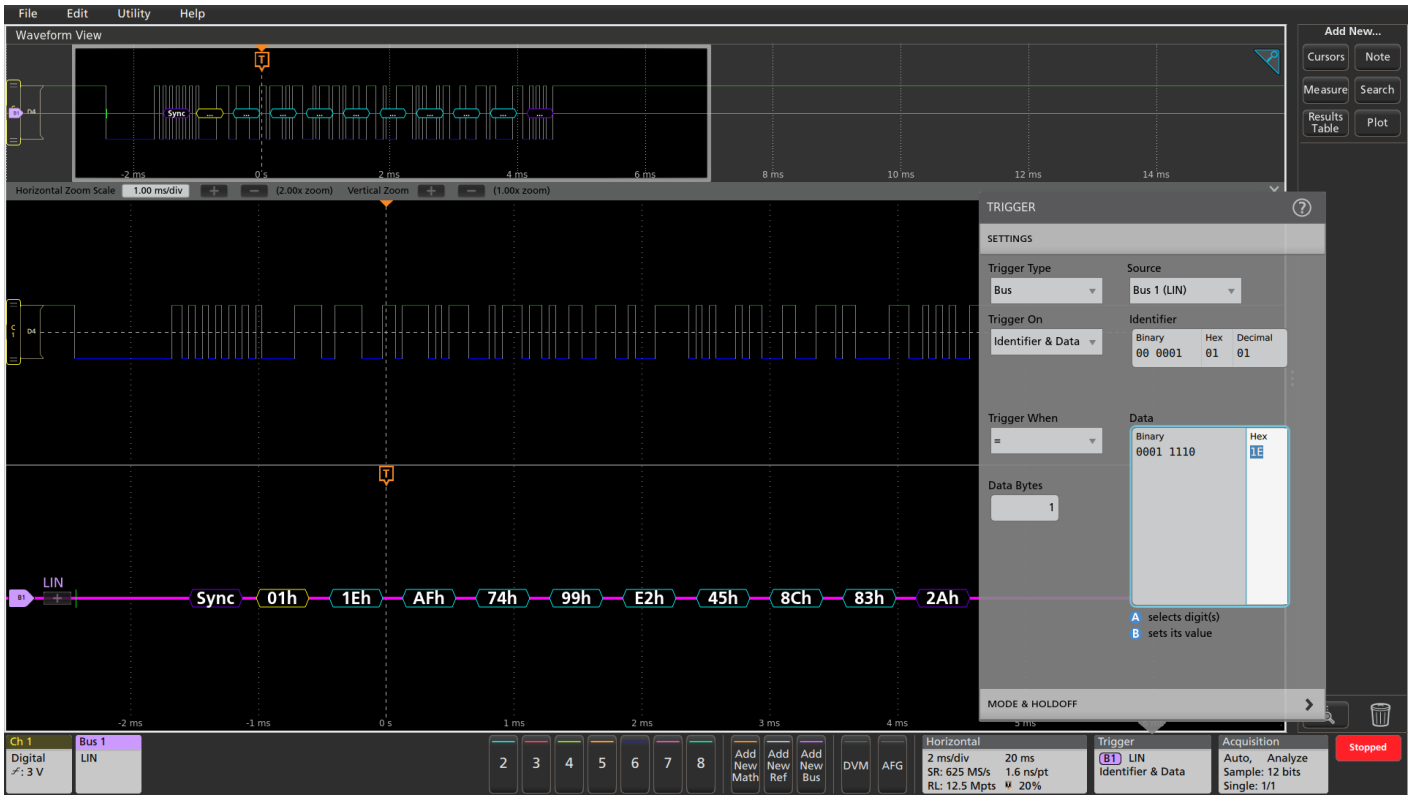
LIN signals can be captured using passive or active analog probes, but digital logic probes can also be used for acquiring LIN signals.



INTERPRETING THE LIN BUS

The decoded bus waveform graphically indicates the different elements of a LIN message.

LIN BUS ELEMENT	INDICATED BY
Start of Frame is indicated by a vertical green bar.	
Sync is shown in a purple box.	
Identifiers are shown in yellow boxes. Identifier values can be displayed in either hex, binary, or decimal.	
Data is shown in cyan boxes. Data values can be displayed in either hex or binary.	
Checksum values are shown in purple boxes (or red boxes, in case of errors).	



TRIGGERING ON LIN BUS ACTIVITY

With the LIN bus properly set up, the oscilloscope will be able to capture all of the input signals, based on the occurrence of a bus trigger event. In this example, the oscilloscope has triggered when the identifier 01 hex is followed by a data value of 1E hex.

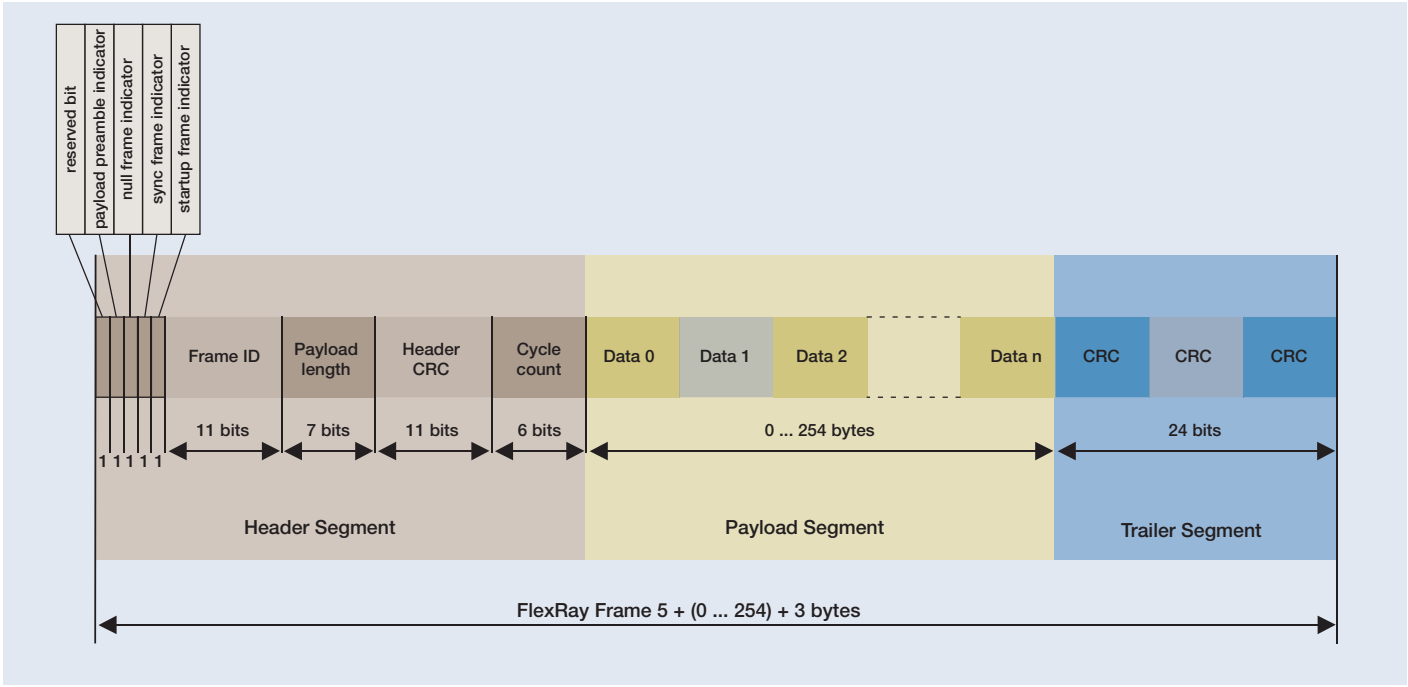
The full LIN bus triggering capabilities include the following trigger types:

TRIGGER ON	DESCRIPTION
Sync	Any sync field
Identifier	Trigger on a specific identifier
Data	Trigger on specific data values or data ranges
Identifier & Data	Trigger on a combination of both identifier and data
Wakeup Frame	Any wakeup frame
Sleep Frame	Any sleep frame
Error	Sync errors, ID parity errors, or checksum errors

These trigger types allow you to isolate different types of events a LIN bus and use them as triggers to view system activity. And with the other advanced serial features found in Tektronix oscilloscopes such as results tables and Wave Inspector search, you can easily debug LIN based automotive designs.

FlexRay

As cars get smarter and electronics find their way into more and more automotive applications, manufacturers are finding that existing automotive serial standards such as CAN and LIN do not have the speed, reliability, or redundancy required to address X-by-wire applications such as brake-by-wire or steer- by-wire. Today, these functions are dominated by mechanical and hydraulic systems. In the future they will be replaced by a network of sensors and highly reliable electronics that will not only lower the cost of the automobile, but also significantly increase passenger safety due to intelligent electronic based features such as anticipatory braking, collision avoidance, adaptive cruise control, etc.



HOW IT WORKS

FlexRay is a differential bus running over either a Shielded Twisted Pair (STP) or an Un-shielded Twisted Pair (UTP) at speeds up to 10 Mb/s, significantly faster than LIN's 20 kb/s or CAN's 1 Mb/s rates. FlexRay uses a dual channel architecture which has two major benefits. First, the two channels can be configured to provide redundant communication in safety critical applications such as X-by-wire to ensure the message gets through. Second, the two channels can be configured to send unique information on each at 10 Mb/s, giving an overall bus transfer rate of 20 Mb/s in less safety-critical applications.

FlexRay uses a time triggered protocol that incorporates the advantages of prior synchronous and asynchronous protocols via communication cycles that include both static and dynamic frames. Static frames are time slots of predetermined length allocated for each device on the bus to communicate during each cycle. Each device on the bus is also given a chance to communicate during each cycle via a Dynamic frame which can vary in length (and time). The FlexRay frame is made up of three major segments; the header segment, the payload segment, and the trailer segment. Each segment is made up of one or more components:

HEADER SEGMENT COMPONENTS	DESCRIPTION
Indicator Bits	The first five bits indicate the type of frame being transmitted. Choices include Normal, Payload, Null, Sync, and Startup.
Frame ID	Defines the slot in which the frame should be transmitted. Frame IDs range from 1 to 2047 with any individual frame ID being used no more than once on each channel in a communication cycle.
Payload Length	Indicates how many words of data are in the payload segment
CRC	Cyclic redundancy check (CRC) code calculated over the sync frame indicator, the startup frame indicator, the frame ID and the payload length
Cycle Count	The value of the current communication cycle, ranging from 0-63.

PAYLOAD SEGMENT COMPONENTS	DESCRIPTION
Data	The data field contains up to 254 bytes of data. For frames transmitted in the static segment the first 0 to 12 bytes of the payload segment may optionally be used as a network management vector. The payload preamble indicator in the frame header indicates whether the payload segment contains the network management vector. For frames transmitted in the dynamic segment the first two bytes of the payload segment may optionally be used as a message ID field, allowing receiving nodes to filter or steer data based on the contents of this field. The payload preamble indicator in the frame header indicates whether the payload segment contains the message ID.

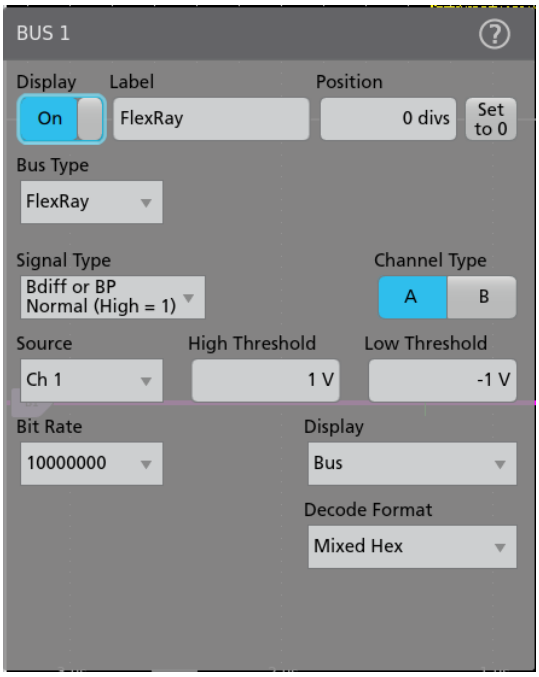
TRAILER SEGMENT COMPONENTS	DESCRIPTION
CRC	Cyclic redundancy check (CRC) code calculated over all of the components of the header segment and the payload segment of the frame.

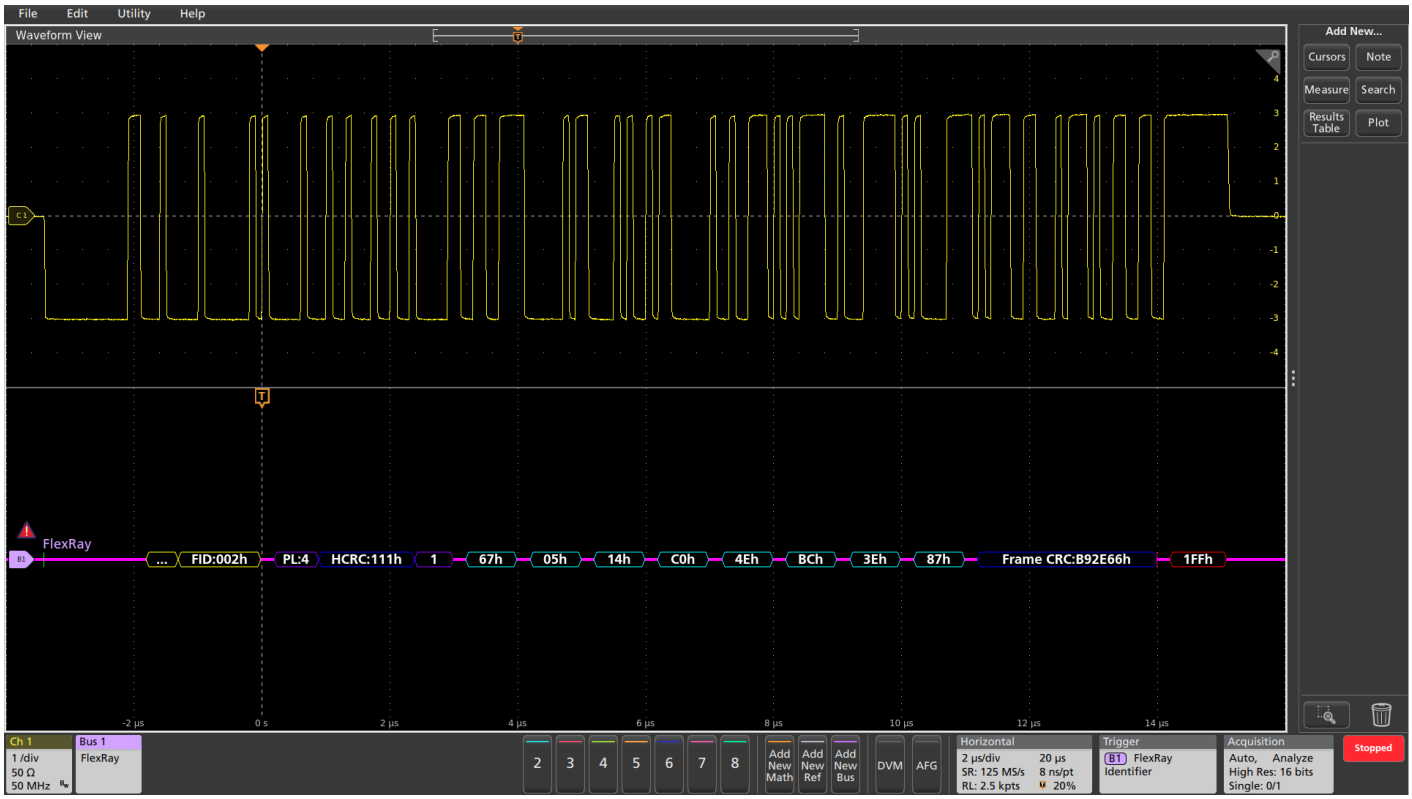
Dynamic frames have one additional component that follows the Trailer CRC called the Dynamic Trailing Sequence (DTS) that prevents premature channel idle detection by the bus receivers.

SETTING UP FLEXRAY BUS DECODING

To set up decoding, you must specify some basic parameters describing the bus:

- Specify the FlexRay channel A or B
- Type of signal we're probing (differential, half the differential pair, or the logic signal between the controller and the bus driver)
- Voltage thresholds. FlexRay requires two thresholds to be set when looking at non-Tx/Rx signals as it is a three-level bus. This enables the oscilloscope to recognize Data High and Data Low as well as the idle state where both signals are at the same voltage.
- Bit rate





DECODING AND TRIGGERING ON FLEXRAY

Once the bus is set up the oscilloscope will be able to isolate, capture, and display specific FlexRay bus events, as well as any other coincident signals. Such a time-correlated display allows you to verify causes and effects in the design. In this example the oscilloscope was set to trigger on the Frame ID value 002 hex.

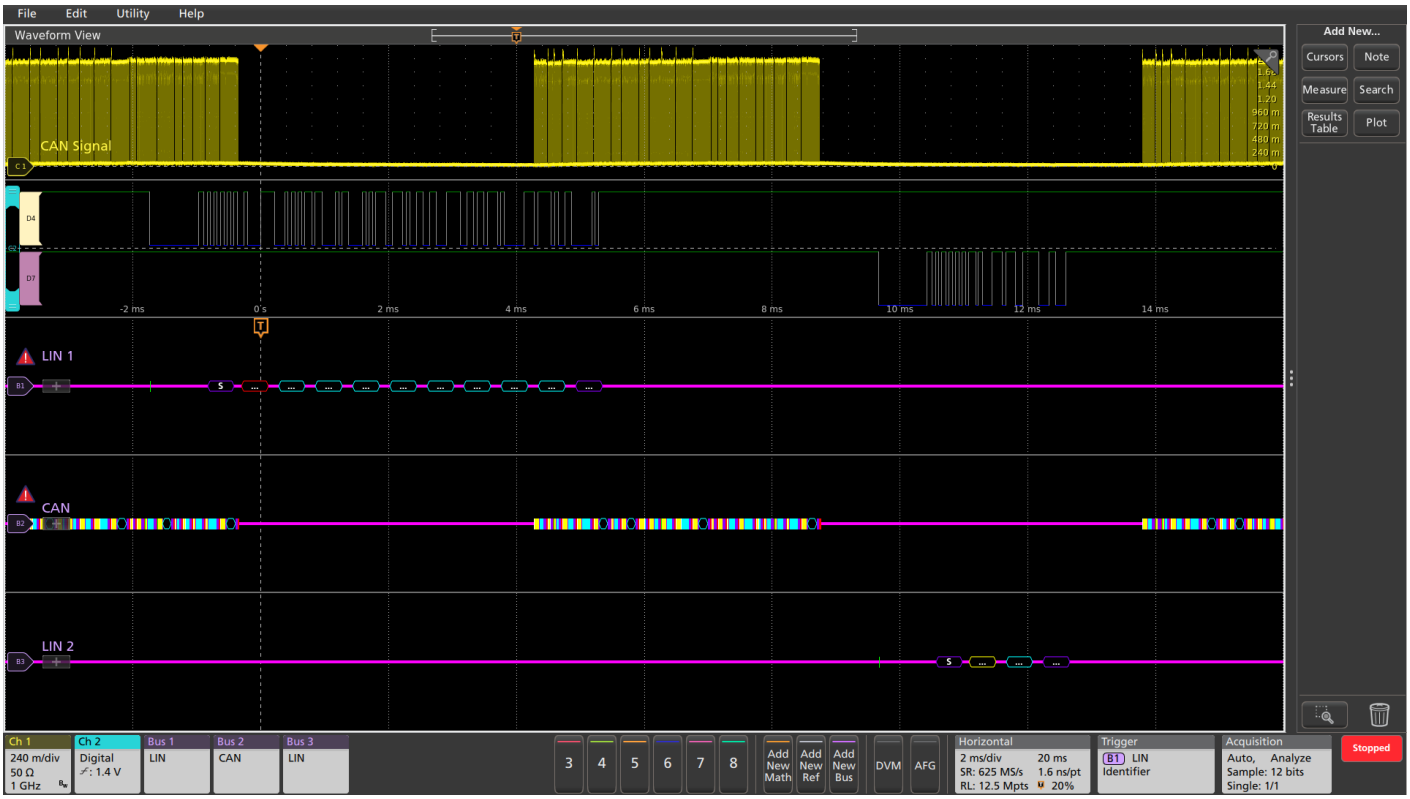
The oscilloscope's FlexRay triggering capability includes the following types:

TRIGGER ON	DESCRIPTION
Start of Frame	Triggers on the trailing edge of the Frame Start Sequence (FSS)
Indicator Bits	Normal, Payload, Null, Sync, or Startup frames
Identifier	Specific Frame IDs or a range of Frame IDs
Cycle Count	Specific Cycle Count values or a range of Cycle Count values
Header Fields	Combination of user specified values in any or all of the header fields including the Indicator Bits, Frame ID, Payload Length, Header CRC, and Cycle Count
Data	Trigger on up to 16 bytes of data. Data window can be offset by a user specified number of bytes in a frame with a very long data payload. Desired data can be specified as a specific value or a range of values
Identifier & Data	Trigger on a combination of Frame ID and data
End of Frame	Trigger on static frames, dynamic frames, or all frames
Error	Trigger on different error types including Header CRC errors, Trailer CRC errors, Null frame errors, Sync frame errors, and Startup frame errors

But how many of the events occurred? To find all of the bus events that meet a specific search criteria, you can use automated Wave Inspector search. The setup is similar to the bus trigger setup, allowing the oscilloscope to find and mark all of the specified bus events.

In the example above the oscilloscope was set up to trigger on a specific Frame ID. It captured and decoded approximately 80 FlexRay frames. Then Wave Inspector search was set up to go through the acquisition and and marked 49 occurrences within a range of data values. Each of the data values in the specified range is shown with the pink bracket icon. Using the arrow keys, you can instantly navigate between marked values.

And all of this was done with only 250,000 point record lengths. The 5 Series MSO, for example, can capture 62.5 Mpoints with standard record length, or 125 M points when equipped with extended record length.



DECODING MULTIPLE BUSES AT ONCE

A powerful feature of the oscilloscope is the ability to define and decode many serial buses simultaneously. Going back to our earlier example with CAN bus; now imagine that the window controls are operated by a LIN bus. When the driver presses the Passenger Window Down control, a message is initiated on a LIN bus in the driver door, passed through a central CAN gateway and then sent on to another LIN network in the passenger door. In this case, we can trigger on the relevant message on one of the buses and capture and decode all three buses simultaneously, making it exceptionally easy to view traffic as it goes from one bus to another through the system. In this example, the scope has triggered on the first LIN message and captured all three buses.

Appendix A

TEKTRONIX OFFERS A RANGE OF MODELS TO MEET YOUR NEEDS AND YOUR BUDGET:

	MSO/DPO70000 SERIES	DPO7000C SERIES	5 SERIES MSO	MSO/DPO5000 SERIES	MDO4000C SERIES	MDO3000 SERIES	MSO/DPO2000 SERIES
Bandwidth	33 GHz, 25 GHz, 23 GHz, 20 GHz, 16 GHz, 12.5 GHz, 8 GHz, 6 GHz, 4 GHz	3.5 GHz, 2.5 GHz, 1 GHz, 500 MHz	2 GHz, 1 GHz, 500 MHz, 350 MHz	2 GHz, 1 GHz, 500 MHz, 350 MHz	1 GHz, 500 MHz, 350 MHz, 200 MHz	1 GHz, 500 MHz, 350 MHz, 200 MHz, 100 MHz	200 MHz, 100 MHz, 70 MHz
Analog Channels	4	4	4, 6, 8	4	4	2 or 4	2 or 4
Digital Channels	16 (MSO)	--	8 to 64 (opt.)	16 (MSO)	16 (opt.)	16 (opt.)	16 (MSO)
Spectrum Analyzer Channels	--	--	--	--	1 (opt.)	1	--
Record Length (All Channels)	Up to 62.5 M (std.) Up to 250 M (opt.)	25 M (std.) Up to 125 M (opt.)	62.5 M (std.) 125 M (opt.)	25 M (std.) Up to 125 M (opt.)	20 M	10 M	1 M
Sample Rate (Analog)	Up to 100 GS/s	Up to 40 GS/s	Up to 6.25 GS/s	Up to 10 GS/s	Up to 5 GS/s	Up to 5 GS/s	1 GS/s
Color Display	12.1 in. XGA	12.1 in. XGA	15.6 in. HD	10.4 in. XGA	10.4 in. XGA	9 in. WVGA	7 in. WQVGA
Serial Bus Triggering and Analysis	I^2C SPI RS-232/422/485/ UART CAN LIN FlexRay USB 2.0 10/100BASE-T Ethernet MIL-STD-1553 8b/10b decoding D-PHY MIPI decoding PCI Express decoding	I^2C SPI RS-232/422/485/ UART CAN LIN FlexRay USB 2.0 10/100BASE-T Ethernet MIL-STD-1553 8b/10b decoding D-PHY MIPI decoding PCI Express decoding	I^2C SPI RS-232/422/485/ UART CAN LIN FlexRay USB 2.0 10/100BASE-T Ethernet I^2S/LJ/RJ/TDM	I^2C SPI RS-232/422/485/ UART CAN LIN FlexRay USB 2.0 10/100BASE-T Ethernet MIL-STD-1553 8b/10b decoding D-PHY MIPI decoding PCI Express decoding	I^2C SPI RS-232/422/485/ UART CAN CAN FD LIN FlexRay USB 2.0 I^2S/LJ/RJ/TDM MIL-STD-1553	I^2C SPI RS-232/422/485/ UART CAN CAN FD LIN FlexRay USB 2.0 I2S/LJ/RJ/TDM MIL-STD-1553	I^2C SPI RS-232/422/485/ UART CAN LIN
Number of Simultaneously Displayed Serial Buses	16	16	Essentially unlimited	16	3	2	2

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