Evolution of (D)CAN

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This article describes the development history of CAN and emphasizes the differences between CAN CC (classic), CAN FD (flexible data rate), and CAN XL (extended data-field length) with respect to DCAN IP cores from Digital Core Design (DCD).

To understand the current state of CAN developments, we must look back at the beginnings. As a proud member of the DCD's R&D team, I am part of a group with extensive experience in developing CAN IP (intellectual property) cores. Let me guide you through a brief history of CAN, focusing on our contributions with DCAN, DCAN FD, and the latest DCAN XL IP cores.

The dawn of (D)CAN

Developed out of the need for real-time control and reliable data transmission, CAN (now called CAN CC (classic)) emerged as a pioneer in networking technology. The protocol was officially released in 1986 at the Society of Automotive Engineers (SAE) conference in Detroit (USA). Bosch published the first CAN specification in 1991.

CAN CC features a maximum payload size of 8 byte and supports bit rates of up to 1 Mbit/s. Unlike in other communication networks, CAN frames are not dedicated to a certain receiving node. CAN enables broadcast communication using data/remote frames with a unique identifier. The identifier indicates the content and defines the network access priority. The CAN CC protocol supports two CAN data frame formats. Basically, they only differ in the length of the CAN identifier. The CAN CC base frame format (CBFF) supports the 11-bit CAN identifier and the CAN CC extended frame format (CEFF) supports the 29-bit CAN-identifier.

CAN CC is renowned for its sophisticated error detection and indication capabilities, high immunity to electromagnetic interference, automatic retransmission of corrupted frames, distinction between temporary errors and permanent node failures, and system-wide data consistency checks. Each CAN node has to check, if the network is idle before starting transmission. The network access is managed via a serial communication protocol called Carrier Sense Multiple Access/Collision Detection with Non-Destructive Arbitration. This protocol ensures that data/remote frame collisions are avoided through bit-wise arbitration without any loss of time.

The AUI (attachment unit interface) of CAN CC provides two possible states: "dominant" and "recessive." These states usually (but not always) correspond to logic "zero" and "one," respectively. The network logic employs a "wired-AND" mechanism, where dominant bits (zeros) overwrite recessive bits (ones). If all nodes transmit recessive bits, the network remains in a recessive state. However, if even a single node transmits dominant bits, it forces the network into a dominant state. This mechanism is crucial for arbitration.

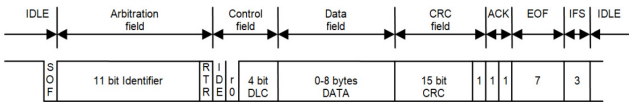

Figure 1: CAN CC base frame format (Source: DCD)

Figure 1 illustrates the CAN CC data frame in the CAN CC base frame format. It is composed of several fields, each with a specific role:

1. *Start of frame (SOF):* A single dominant bit indicating the beginning of a frame.
2. *Arbitration field:* Contains the identifier and the RTR (remote transmission request) bit. The RTR bit allows for the transmission of remote frames, which carry the data length code (DLC) for the requested frame but contain no data.
3. *Control field:* Includes the DLC, which defines the number of data bytes sent in the frame. It also contains ▷

either the IDE (ID extension) bit and one reserved bit for future use or two reserved bits, depending on the frame format. Reserved bits must be sent as dominant.
4. *Data field:* The actual data payload of the frame.
5. *CRC field:* Comprises the CRC (cyclic redundancy check) sequence and the CRC delimiter. The CRC is calculated over the destuffed bit sequence from the SOF to the end of the data field. The CRC delimiter is a single recessive bit.
6. *ACK field:* Consists of the ACK slot and delimiter. The transmitter sends two recessive bits, while the receiver acknowledges correct frame reception by sending a dominant bit during the ACK slot. If any node detects an error, it signals a corrupted message in the ACK field, preventing defective nodes from locking the network.
7. *End of frame (EOF):* Seven recessive bits signaling the end of a frame.

After the EOF, an interframe space of at least three bit times is required before the network becomes idle and ready for the next transmission.

Error handling and synchronization

CAN CC handles errors using two types of error frames:
- *Active error flag:* Six consecutive dominant bits sent after detecting an error.
- *Passive error flag:* Six consecutive recessive bits sent after detecting an error.

These error flags increment internal error counters, which can cause defective nodes to enter an error-passive state and eventually a bus-off state, requiring reconfiguration before they can resume network traffic.

Bit stuffing and bit timing

To maintain data integrity, CAN CC employs bit stuffing. After five consecutive bits of the same value, the transmitter inserts a bit of the opposite value. Error and overload flags are the only exception, containing six consecutive bits of the same value. The bit symbols are NRZ-coded (non-return-to-zero). CAN CC synchronizes frame transfers by aligning all nodes at the start of each frame with the first falling edge of the SOF bit, a process known as hard synchronization. To ensure accurate sampling throughout the entire data/remote frame, CAN nodes re-synchronize on each recessive-to-dominant edge, necessitating bit stuffing.

The CAN CC physical coding sublayer (PCS) divides the bit time into four non-overlapping time segments to manage synchronization and compensate for signal delays. Each time segment is constructed from an integer multiple of a time quantum (t_q). The time quantum is the smallest discrete timing resolution used by the CAN CC node.

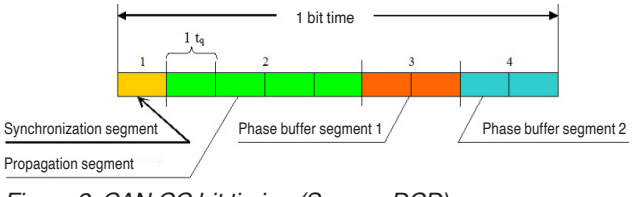

Figure 2: CAN CC bit timing (Source: DCD)

Figure 2 shows the CAN CC bit timing:
1. *Synchronization segment:* This 1-t_q segment ensures that any bit state change between the previous and current bit occurs within this segment. It allows receiving nodes to synchronize with the network state change.
2. *Propagation segment:* Compensates for signal delays across the network and must be at least one t_q.
3. *Phase buffer segment 1:* Used to compensate for edge phase errors. It must be at least one t_q, but can be lengthened during resynchronization to account for oscillator tolerances among different CAN nodes. The extent of lengthening is limited by the synchronization jump width (SJW).
4. *Phase buffer segment 2:* Also used to compensate for edge phase errors. It must be at least one t_q, but can be shortened during resynchronization to account for oscillator tolerances. The extent of shortening is also limited by the SJW.

The sample point is the moment, when the network level is evaluated and interpreted as the status of the respective bit. It is located between the phase buffer segment 1 and phase buffer segment 2.

In 2024, Digital Core Design is celebrating its 25th anniversary. Founded in 1999 and after five years, DCD's team has introduced the DCAN IP, a CAN CC IP core. Since then, DCAN has been integrated into millions of vehicles worldwide. Thus, the "CAN journey" lasts for DCD for more than two decades. However, CAN CC has limitations, such as a small payload and a limited transmission speed. These drawbacks led to the development of CAN FD (flexible data rate), which addresses these issues and enhances the protocol's capabilities.

Enter CAN FD

The next iteration of CAN technology introduced the CAN FD (flexible data rate) frame format, which supports bit rates higher than 1 Mbit/s, reaching up to 8 Mbit/s, and allows payloads up to 64 byte. CAN FD maintains full backward compatibility with CAN CC frames, with the CAN FD frames distinguished by the FDF (flexible data format) formerly reserved in CAN CC.

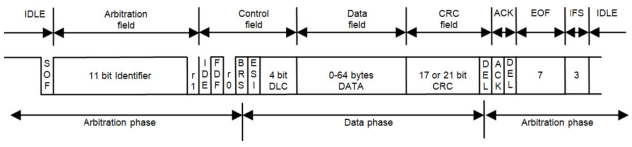

Figure 3: CAN FD base frame format (Source: DCD)

Figure 3 shows the CAN FD base frame format. While the order and number of fields in the frame remain the same as in CAN CC, the lengths of certain fields have been adjusted to accommodate the new features and enhancements. The key features and improvements include:
- *Bit rate switch (BRS) bit:* This bit determines whether the bit rate is switched within the frame. By enabling higher bit rates, CAN FD can transmit more data within the same time frame, preventing larger data packets from overloading the network.

- *Error state indicator (ESI) bit:* This bit indicates whether the sender (transmitter) of the message is in an active error node or a passive error node, providing better error management.
- *Extended data length code (DLC):* The values encoded by the DLC have been extended to indicate longer data payloads. This allows for more efficient data transmission, especially for applications requiring larger payloads.
- *CRC polynomials:* The CRC adjustments ensure data integrity across varying payload sizes.
  - 17-bit CRC: Applied to CAN FD data frames with a data field up to 16 byte.
  - 21-bit CRC: Utilized for larger data fields in CAN FD data frames.

The rest of the frame structure remains similar to CAN CC, allowing CAN FD devices to connect to the same physical network, including use of the same transceivers, connectors, and cables. CAN FD does not support remote frames.

In 2016, to keep pace with the rapidly evolving automotive industry, DCD has designed the DCAN FD based on the Bosch CAN FD specification and the ISO 11898-1:2015 standard. While the Bosch CAN FD was published in 2012 and the ISO 11898 in 2015, DCD's developments followed closely, ensuring compliant implementation. The DCAN FD also underwent the testing against the ISO 16845-1 conformance test specification. Building upon the base of DCAN IP, the DCAN FD incorporates the new CAN FD features. Despite not being a completely new product, but rather an evolution of the DCAN IP, it achieved significant market success due to its enhanced capabilities and reliability.

The DCAN FD was designed with functional safety in mind, meeting the requirements of ISO 26262. It incorporates essential safety mechanisms to ensure the appropriate functional safety level, developed as a Safety Element out of Context (SEooC), and is ready for ASIL-B (automotive safety integrity level) or higher applications. This was the first DCD's IP designed with functional safety compliance. Leveraging our knowledge and experience, we advanced the DCAN FD to the DCAN FD Full. This IP brought following improvements:

- *User experience:* Enhanced user experience with more intuitive interfaces.
- *Hardware-filtering capabilities:* Support for up to 128 base ID filters and up to 64 extended ID filters.
- *Data throughput:* Increased data throughput with two configurable receive FIFOs, up to 32 dedicated transmit buffers, and configurable transmit buffers that can operate in FIFO or queue modes.
- *Event logging:* Dedicated transmit event FIFO and time-stamping according to CiA 603.
- *Data-processing time:* Optimized data processing with two clock domains – one for the CAN clock and another for the CPU clock.
- *Functional safety enhancements:* Further safety improvements ensuring compliance with the latest standards.

At that time, the DCAN FD Full represented the most advanced CAN IP. However, the time marched on, and we faced new challenges: Accommodating larger data packets and achieving faster transmission speeds to meet future demands.

The advent of CAN XL

As we stepped into 2024, the automotive industry welcomed the advent of CAN XL (extended data-field length), the latest advancement in CAN technology. At DCD, we have announced the release of DCAN XL, which conforms to the updated ISO 11898:2024 standards and the CiA 610-1 specification (in the meantime withdrawn by CiA). This CAN solution represents the pinnacle of DCD's recent achievements and is now available on the market.

The DCAN XL builds on the legacy of our previous CAN solutions and integrates seamlessly into modern automotive networks. It supports the extended payload capacity of up to 2048 byte and can achieve bit rates up to 20 Mbit/s, bridging the gap between CAN FD and Ethernet. DCAN XL also enables to tunnel and to map entire Ethernet frames, thus enhancing data throughput without compromising network timing. At the fifth CAN XL plugfest organized by CAN in Automation (CiA) in Baden-Baden (Germany), DCAN XL has successfully passed the performed interoperability tests within a real CAN XL network.

The key features and enhancements of DCAN XL include:

- *Backward compatibility:* The DCAN XL controller can handle CAN CC and CAN FD frames, ensuring seamless integration with existing systems.
- *Extended payload and bit rates:* With payloads up to 2048 byte and bit rates up to 20 Mbit/s (when using CAN SIC XL transceivers and appropriate topologies), DCAN XL supports higher data transfer requirements.
- *Enhanced CAN-ID field:* The CAN-ID field is divided into an 11-bit priority field and a 32-bit acceptance field (AF), providing improved frame prioritization and acceptance filtering.
- *Protocol-embedded configuration:* CAN XL introduces new configuration options, such as disabling error signaling and enabling PWM (pulse-width modulation) coding, which allows for higher bit rates depending on the physical network design. While PWM is used, the network changes to push-pull type.
- *Improved reliability:* The use of two CRC fields – the 13-bit preface CRC (PCRC) in the control field and the 32-bit frame CRC (FCRC) in the CRC field – ensure enhanced error detection and data integrity. These CRCs can detect any five randomly distributed bit-errors, offering a Hamming distance of 6.

The CAN XL frame structure has been extensively updated compared to CAN CC and CAN FD, yet maintaining backward compatibility. DCD remains committed to provide solutions that meet the evolving demands of the automotive industry.

SOF	Arbitration Field	Control Field	Data Field	CRC Field	ACK Field	EOF

Figure 4: CAN XL frame format (Source: DCD)

The Figure 4 to Figure 8 show the CAN XL data frame and its fields in detail. Described are only the fields newly included in CAN XL.

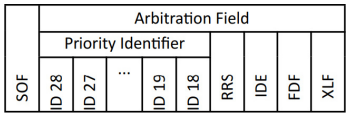

Figure 5: CAN XL arbitration field (Source: DCD)

In the CAN XL data-frame structure, several key bits play crucial roles in determining frame types and priorities. The priority identifier sets the priority for CAN XL data frames, ensuring efficient frame handling based on priority levels. The RRS (remote request substitution) bit, is located at the same bit position as the RTR (remote transmission request) bit in CAN CC data frames and the same as the RRS bit in CAN FD data frames. This ensures consistency and compatibility across different CAN generations. The XLF (extended length frame) bit differentiates between CAN FD and CAN XL data frames. In a CAN XL data frame, the XLF bit is always recessive. When the XLF bit is recessive, the FDF (frame data field) bit is also recessive. This configuration is crucial for distinguishing CAN XL data frames from other frame types within the CAN network.

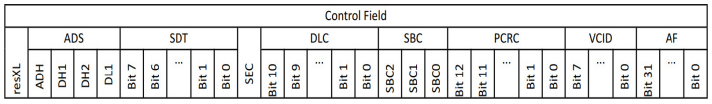

Figure 6: CAN XL control field (Source: DCD)

The resXL bit is reserved for future expansion within the protocol's framework. The arbitration to data sequence (ADS) serves dual purposes:

- Transitioning the bit rate from the nominal bit rate to the CAN XL data bit rate;
- Shifting the CAN transceiver mode from arbitration mode to either data TX mode or data RX mode.

ADS comprises ADH, DH1, DH2, and DL1 bits, as shown in Figure 6. ADH, the final nominal bit time before the beginning of the XL data phase, is transmitted as a recessive bit. Subsequent bits, DH1 and DH2, mark the beginning of the XL data phase, are also transmitted recessively. The bit rate shift occurs precisely between ADH and DH1. Receiver synchronization occurs at the transitions from XLF bit to the preceding resXL bit, and from DH1 and DH2 bits to DL1 bit.

SDT (service data unit type), an 8-bit value, originates from the LLC (logical link control) frame, while the SEC (simple extended content) bit is also passed from the LLC frame.

The data length code (DLC), spanning 11 bits (ranging from 0 to 2047), correlates to a data length between 1 byte and 2048 byte. The stuff bit count (SBC), a 3-bit value, indicates the quantity of dynamic stuff bits within the arbitration field, with values ranging from 0 to 3 (Gray-coded). Preface-CRC (PCRC) sequence, derived from CRC, is calculated over the bit stream encompassing the arbitration field, SDT, SEC bit, DLC, and SBC. Dynamic stuff bits, including up to three preceding the FDF bit, are factored into the calculation, whereas static bits such as SOF, IDE, FDF, XLF, resXL, ADS, and fixed stuff bits are excluded.

VCID (virtual CAN network ID), an 8-bit value, and AF (acceptance field), a 32-bit value, are both passed from the LLC frame.

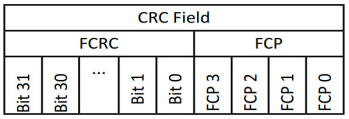

Figure 7: CAN XL CRC field (Source: DCD)

The CRC field contains the frame-CRC (FCRC) sequence and the format check pattern (FCP). The relevant bit stream for the CRC calculation is the bit stream consisting of arbitration field, control field, and data field. It excludes the same static bits as the PCRC. Both dynamic and fixed stuff bits are excluded from the CRC calculation.

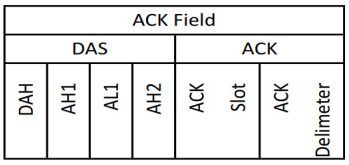

Figure 8: CAN XL ACK field (Source: DCD)

The ACK field encompasses the DAS (data to arbitration sequence), the ACK slot, and the ACK delimiter. Notably, DAH, AH1, AH2, ACK slot, and ACK delimiter bits are transmitted as recessive, while AL1 bit stands as dominant. The DAS serves a dual role:

- Transitioning the bit rate from the XL data bit rate to the nominal bit rate.
- Shifting the CAN transceiver mode from either data TX mode or data RX mode to arbitration mode, if the mode transition occurred in the preceding ADS.

DAS comprises DAH, AH1, AL1, and AH2 bits. DAH, the initial bit following the nominal bit time, marks the end of the XL data phase at the XL data bit rate.

Conclusion

As we reflect the history of CAN, from its beginnings in the 1980s, CAN has remained at the forefront of innovation. The scope of CAN XL exceeds the possibilities of traditional automotive and non-automotive engineering, offering a range of applications that extend beyond conventional boundaries.

Understanding the history of CAN unveils the evolution of Digital Core Design (DCD) and (D)CAN Intellectual Properties (IPs). Our company commemorates its 25th anniversary this year – a quarter-century of innovation. DCD remains committed to provide solutions that meet the evolving demands of the automotive industry. ◀

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