Accessing the shared communication medium

Media
Access
Conntrol

Network-topologies

- Bus
- Ring
- Star
- Tree
- grid, mesh
- fully connected

assessment criteria:
Overhead, latency, tolerance of transmission errors and network partitions

What are the impairments of predicatbilty ?

Load

Failures

Network contention
Arbitration conflicts

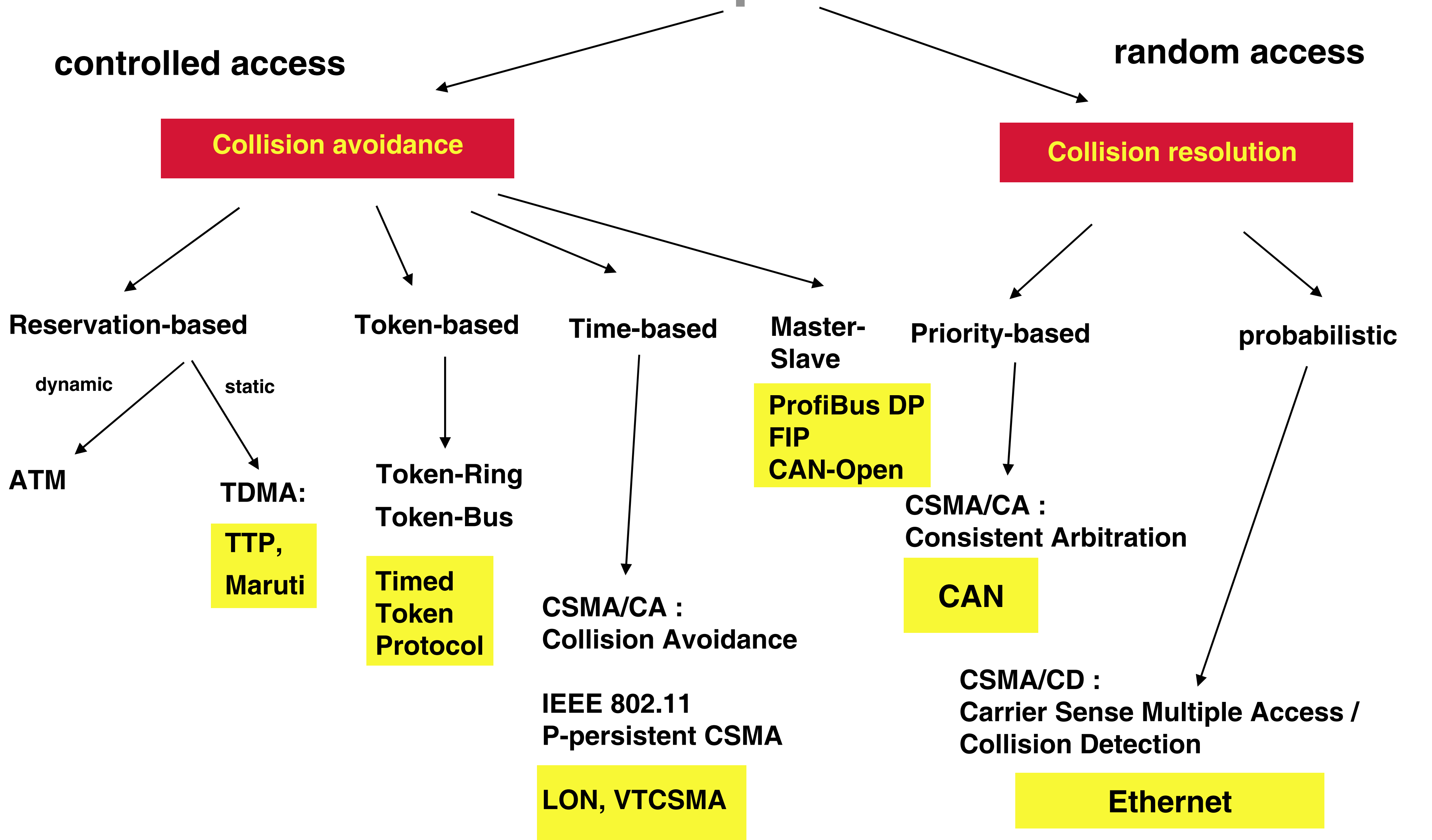
transmission errors,
lost messages

Media Access Control & Logical Link Layer

transfer of data blocks
flow control
fault and error handling
message re-transmissions

Logical Link	**LL -layer**	fault and error treatment, re-transmission flow control
Media Access	**MAC -layer**	access control, arbitration control

MAC-protocols



Controlled Access by Collision Exclusion:

Master/Slave

all control information in one place
maximum of control
easy to change

Global Time

Easy temporal co-ordination

Minimal communication overhead

Token-based

Decentralized mechanism

Integration of critical and non-critical messages

Predictability in random access networks:

probabilistic

very low overhead and latency in low load conditions
very flexible wrt. extensibility
thrashing in high load situations

Collsion avoidance

balances the latency againt the collision probability
maintains a good average throughput in medium load situations
may adapt to high load conditions

Consistent arbitration/Collision Resolution

needs support from the physical layer
maintains a constant throughput in all load conditions
supports sophisticated fault handling

CAN-Bus
Controller Area Network

CAN Milestones

1983	Start of the Bosch internal project to develop an in-vehicle network
1986	Official introduction of CAN protocol
1987	First CAN controller chips from Intel and Philips Semiconductors
1991	Bosch's CAN specification 2.0 published
1991	CAN Kingdom CAN-based higher-layer protocol introduced by Kvaser
1992	CAN in Automation (CiA) international users and manufacturers group established
1992	CAN Application Layer (CAL) protocol published by CiA
1992	First cars from Mercedes-Benz used CAN network
1993	ISO 11898 standard published
1994	1st international CAN Conference (iCC) organized by CiA
1994	DeviceNet protocol introduction by Allen-Bradley
1995	ISO 11898 amendment (extended frame format) published
1995	CANopen protocol published by CiA
2000	Development of the time-triggered communication protocol for CAN (TTCAN)

http://www.can-cia.org/can/protocol/history/index.html

Requirements for the communication system

- Decentralized arbitration mechanism
- Decentralized fault handling
- Low overhead for the host processor

CAN in industrial automation

- **Technical reasons: . . . .**
- **Economic reasons:**

Component Costs
Availability of Components
Standardization

Manufacturers of Fieldbus Components in Germany (Systeme/4/99)

Total	Bitbus	CAN	FIP	Interbus-S	LON	Profibus	CAN + Profibus
229	19	164	7	89	31	119	96

The CAN Standard

Developed by BOSCH, http://www.semiconductors.bosch.de/pdf/can2spec.pdf

CAN Specification 1.2
CAN Specification 2.0

Difference between the specifications mainly is:

- **the different lenth of message identifiers (CAN-ID)**
  - **Standard CAN: 11 Bit IDs (defined in CAN 2.0 A ← 1.2)**
  - **Extended CAN: 29 Bit IDs (defined in CAN 2.0 B)**

CAN-Controller Implementations:

- **Basic CAN: 1 Transmit + 1 Receive (Shadow) Buffer**
- **Extended CAN: 16 Configurable Transmit/Receive Buf.**

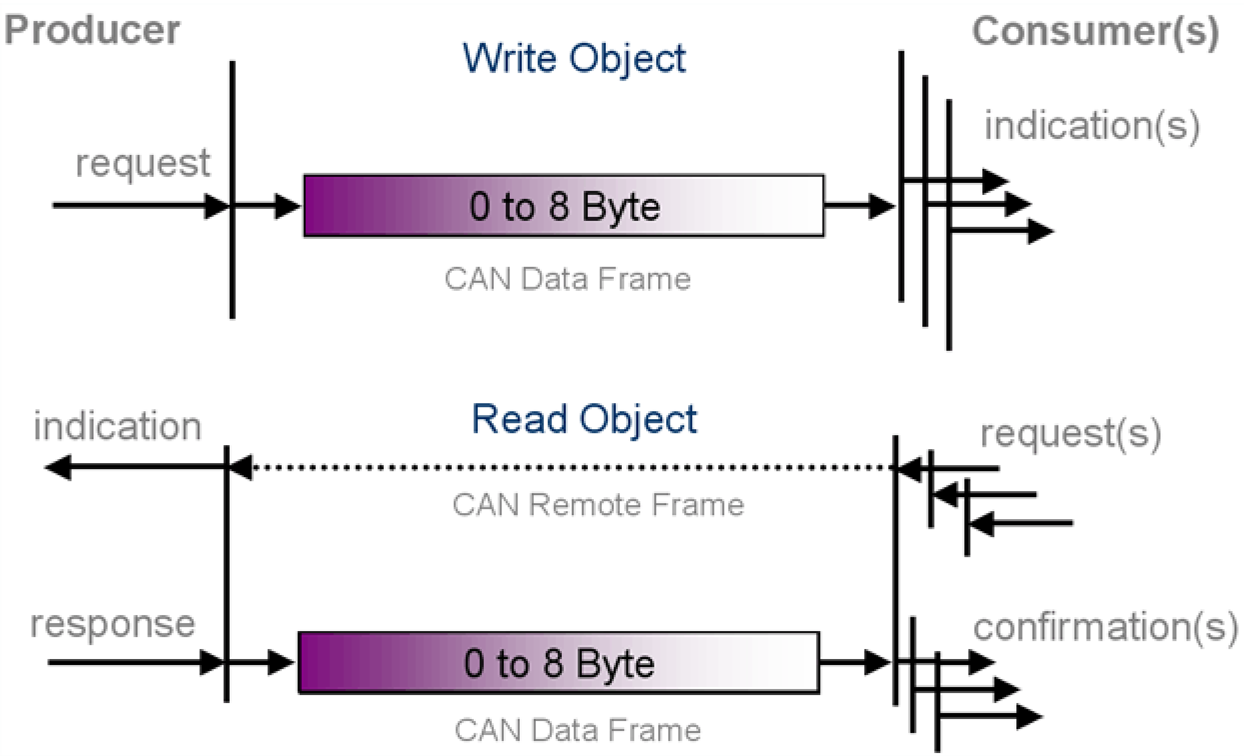
Properties of the CAN-Bus

Arbitration	**Predictable Access to the communication medium**
Elasticity	**Ability to modify or extend the system without affecting already existing parts**
Reliability	**Means to achieve a reliable message transfer**

Basic CAN properties

- Prioritised messages
- Bounded and guaranteed message delay for the highest priority message.
- Constant troughput in all load situations
- Error detection and signalling in the nodes.
- Automatic re-transmission.
- Fail silent behaviour of nodes.
- Consistent message delivery.
- Multicast with time synchronization.

Basic CAN bus Communication Services

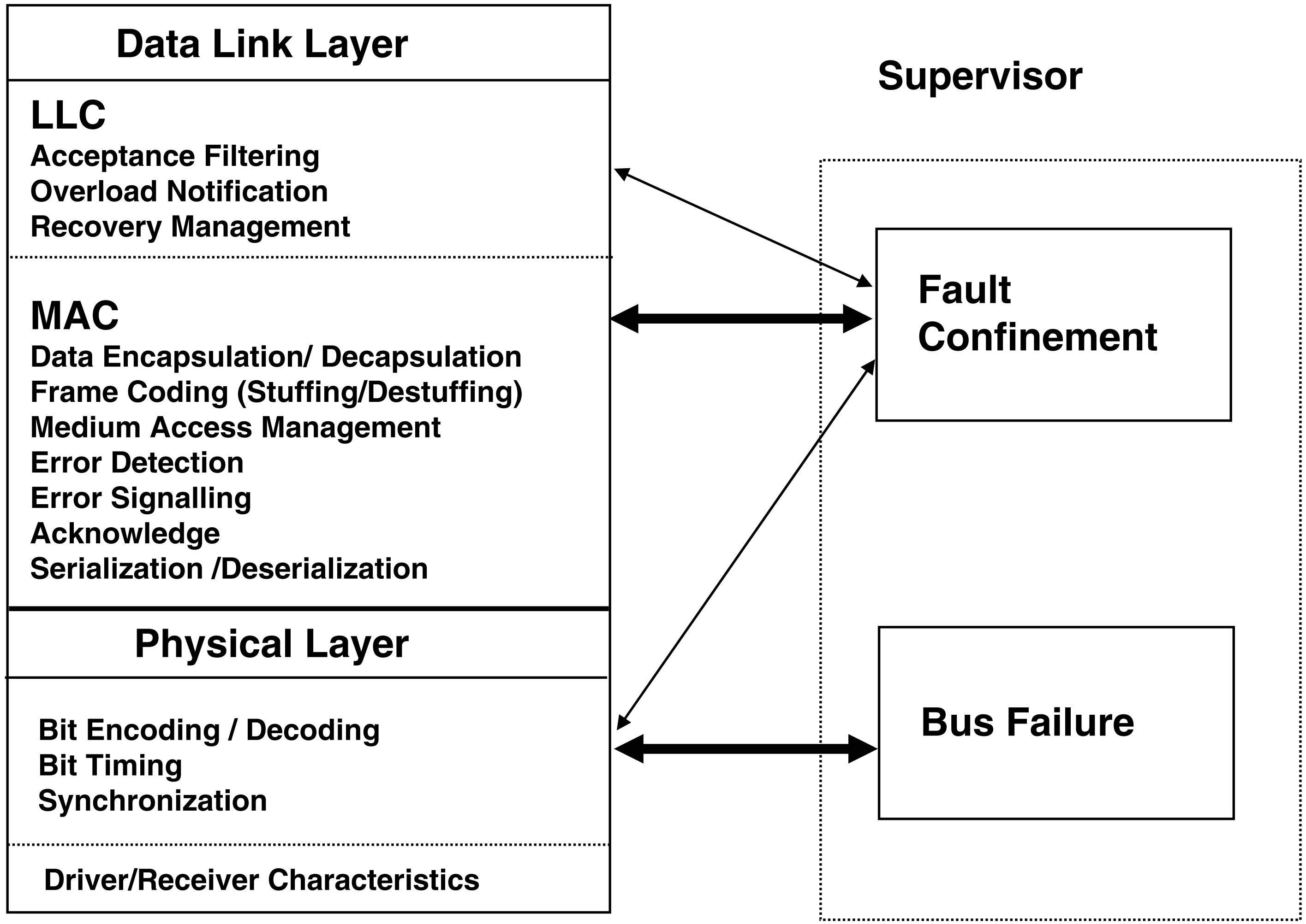


producer initiated communication

consumer initiated ommunication (remote transmit request)

http://www.softing.com/home/en/industrial-automation/products/can-bus/more-can-bus/communication/

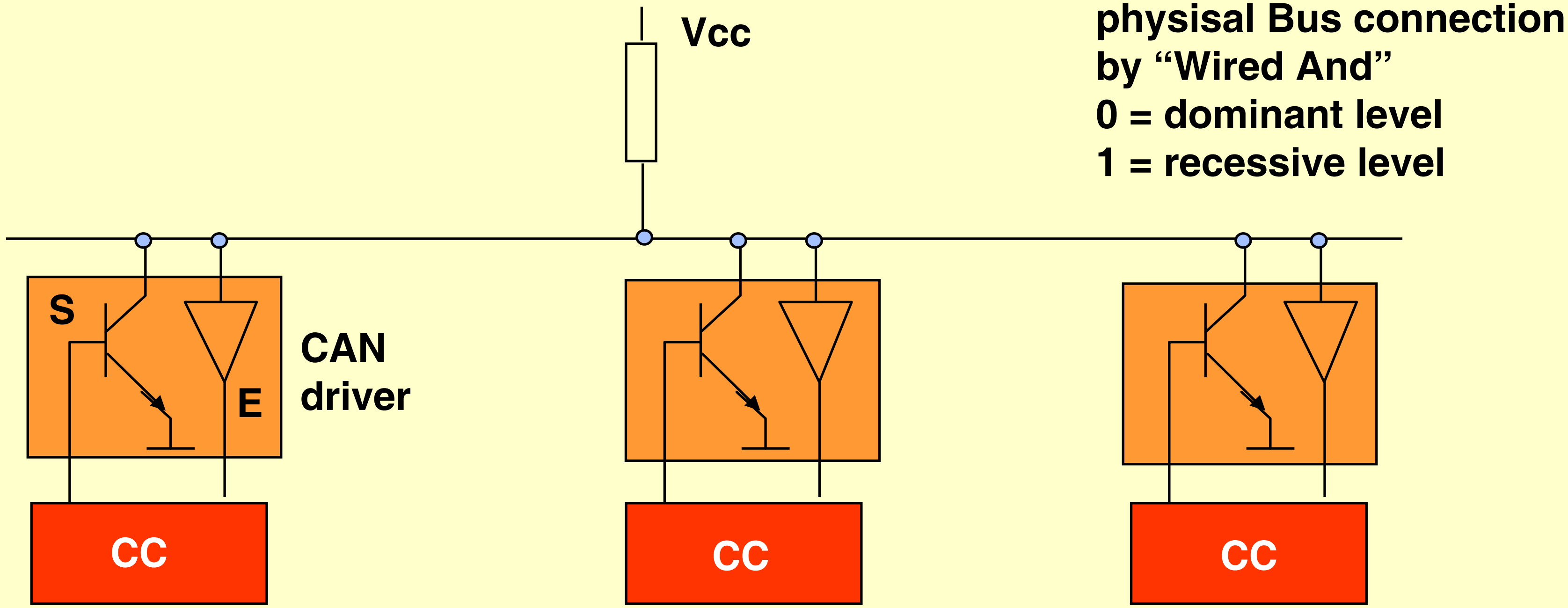
Layers defined by the CAN standard



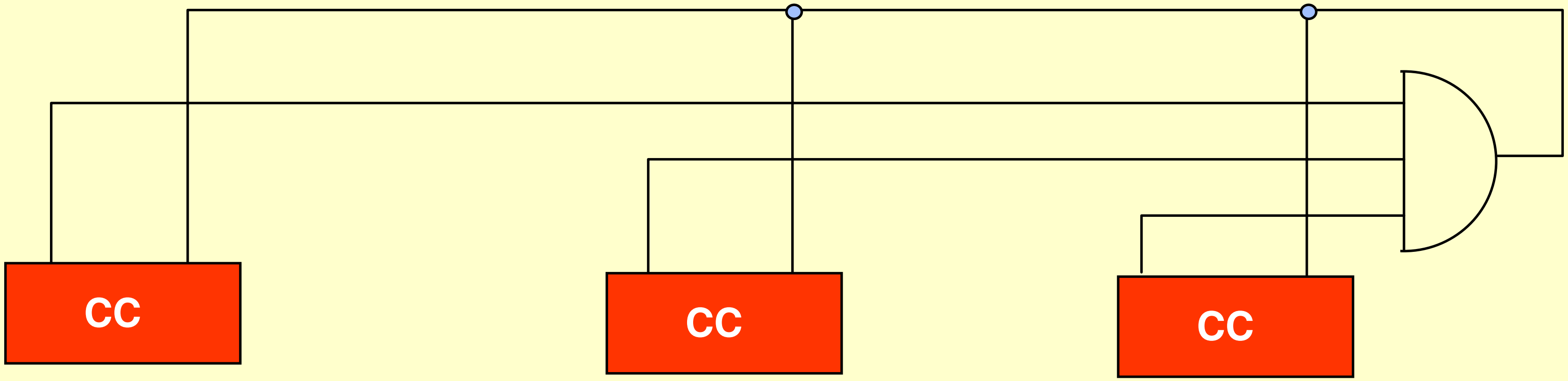
LLC = Logical Link Control
MAC = Medium Access Control

The CAN physical layer

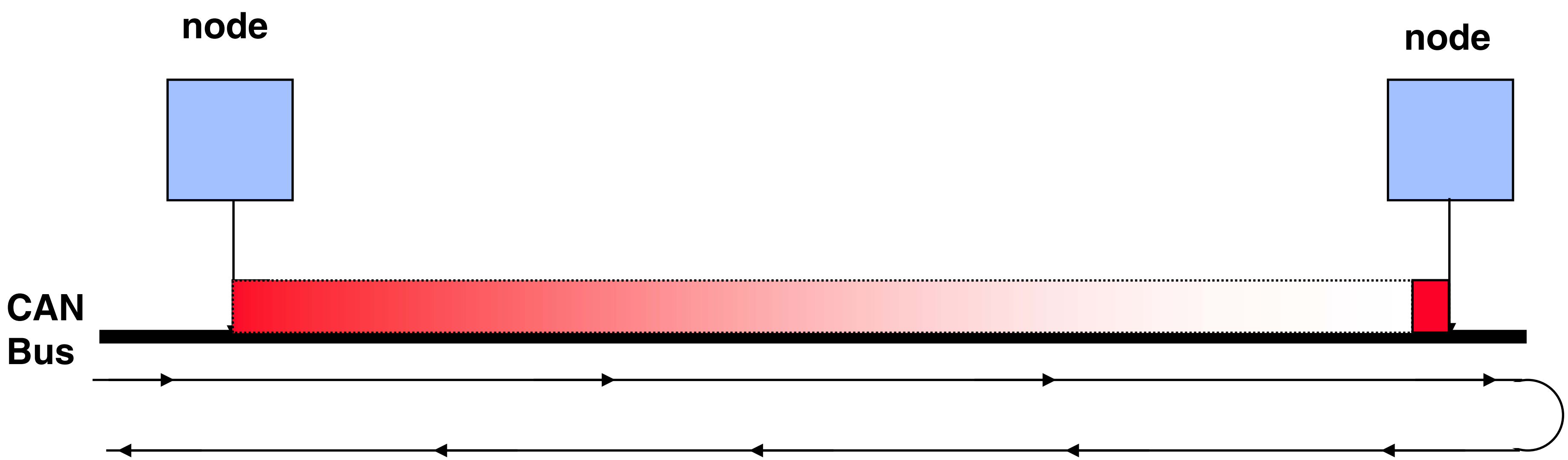
physisal connection



logic equivalent



CAN Bit Synchronisation



After a certain time, all nodes have seen the value of a bit

Bit rate dependend on the length of the bus

Bit Monitoring

CAN transfer rates in relation to the bus length

$$T_d = T_{TT\text{-}delay} + T_{line\ delay}$$

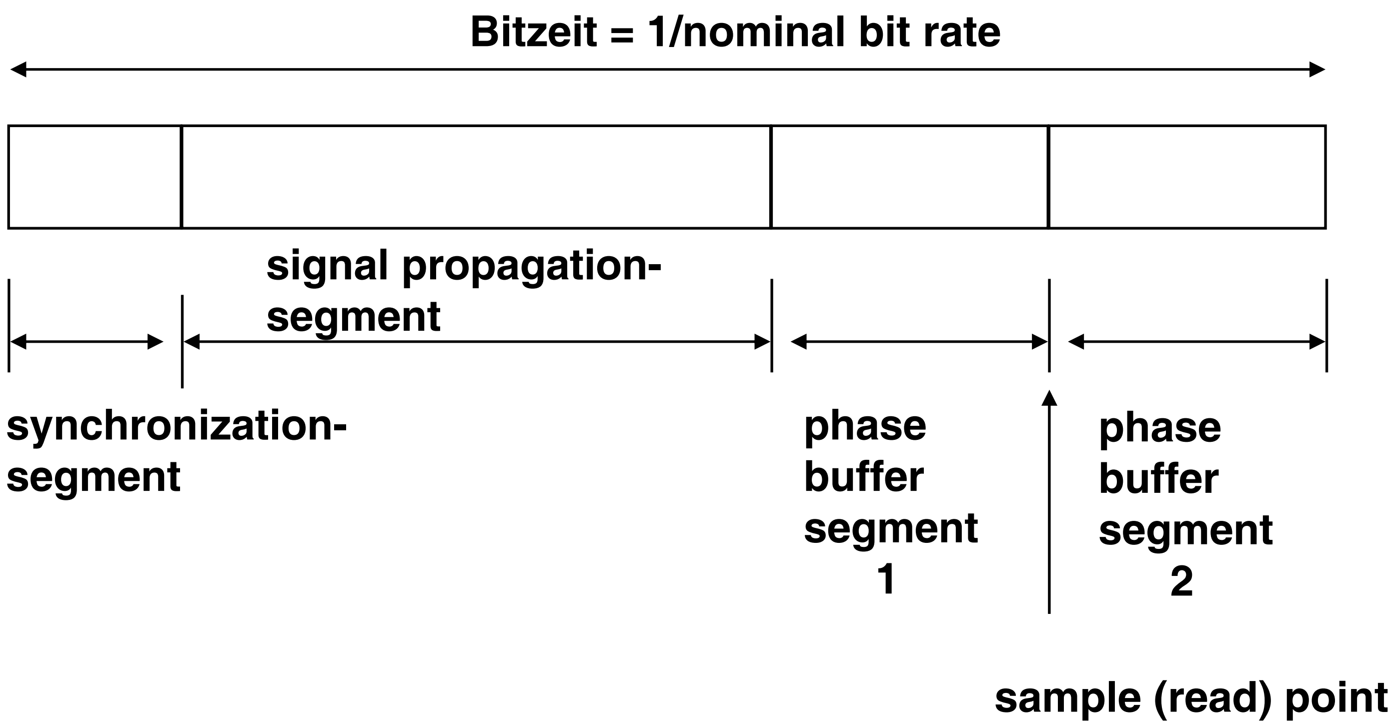
$T_{TT\text{-}delay}$ ~ 100 ns

(driver, transceiver, comparator logic, etc.)

$T_{line\ delay}$ ~ 0,2 m / ns twisted pair

Bitrate (kBits/s)	max. network extension (m)
1000	40
500	112
300	200
200	310
100	640
50	1300

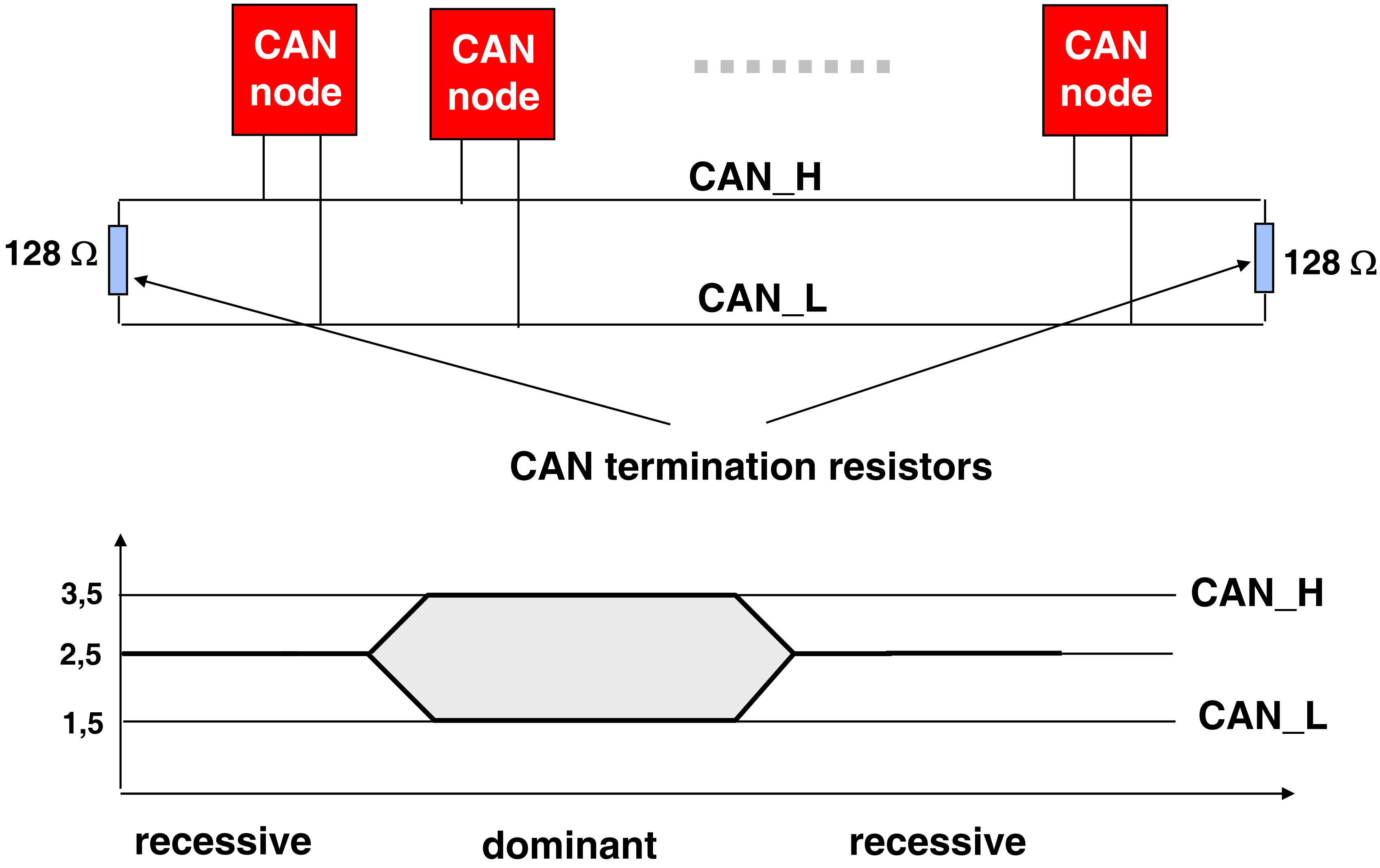
Bit-timing and bit synchronization



Länge der Zeitsegmente werden in Vielfachen einer aus der Oszillatorperiode abgeleiteten Zeiteinheit (time quantum) spezifiziert:

synch.-segment	1	time quanta
sig. propag. seg.	1...8	time quantas
phase buffer seg. 1	1...8	time quantas
phase buffer seg. 2	1...8	time quantas

CAN differential transmission scheme

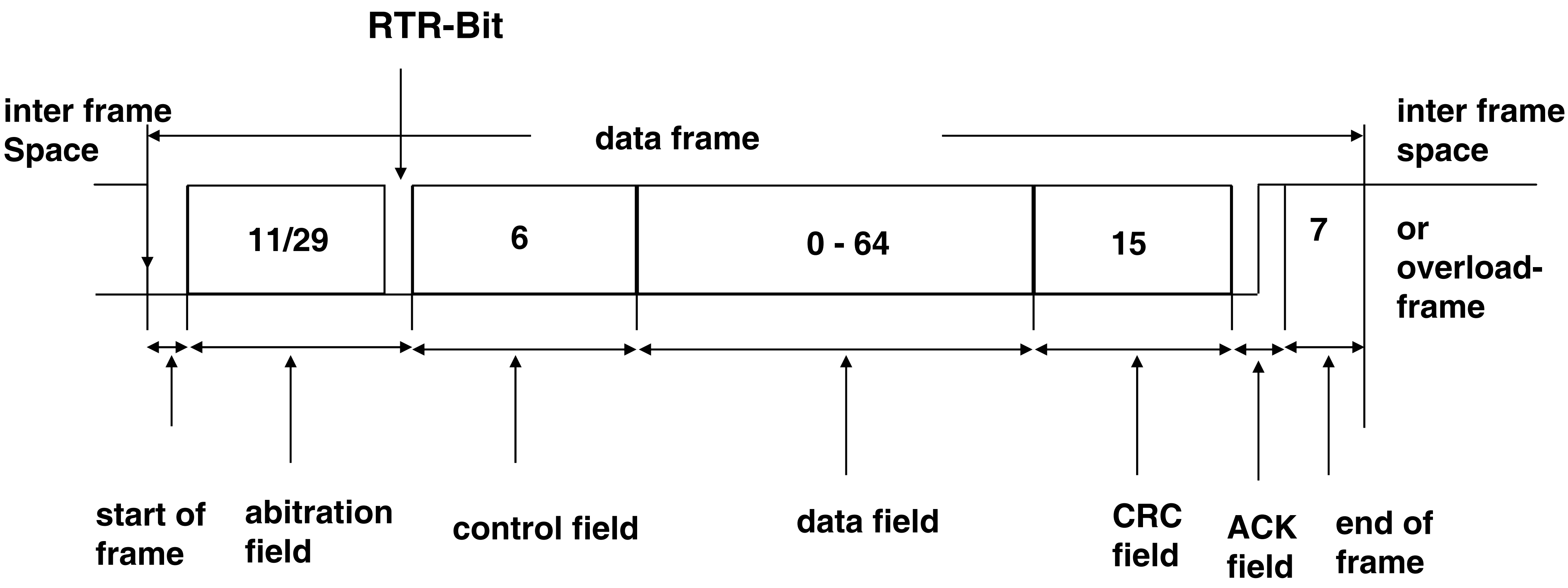


The CAN MAC and Logical Link Control (LLC) levels

Frame types and formats:

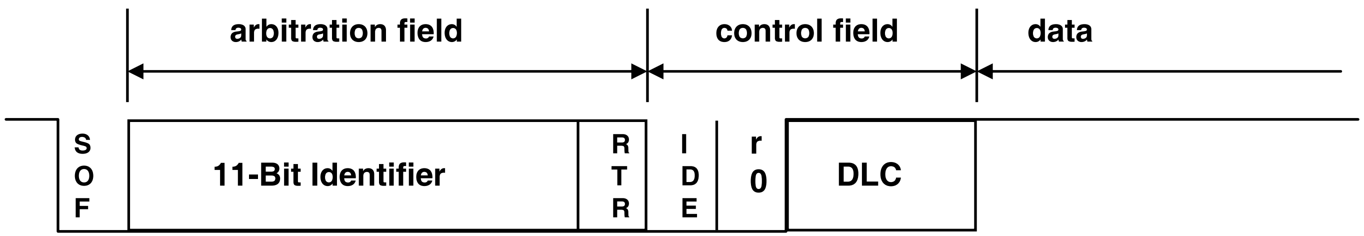
- **Data Frame** normal data transmision initiated by the sender
- **Remote Frame** participant requests frame which is sent with the identical frame ID from some other participant.
- **Error Frame** participant signals an error that it has detected
- **Overload Frame** used for flow control. Results in a delayed sending of the subsequent frame.

CAN Data Frame

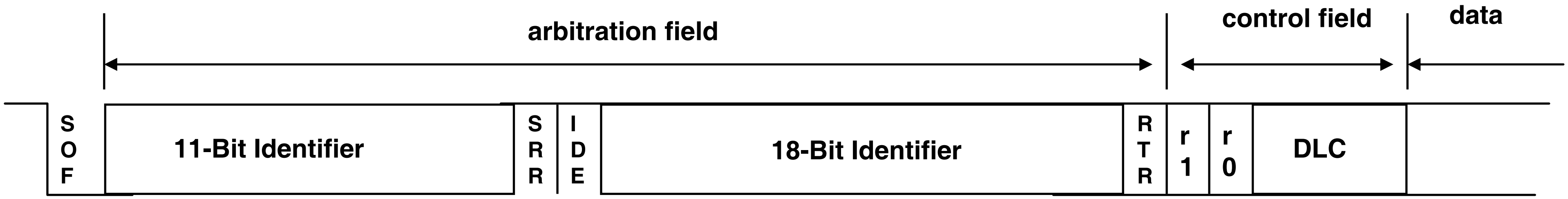


Compatibility between standard and extended frames

Standard Format SF (compatible to CAN Specification 1.2)



Extended Format EF (CAN Specification 2.0)



RTR: Remote Transmissin Request. In Data Frame: RTR = dominant. In Remote Frame: RTR = recessive.
In the EF, the SSR-Bit has the funktion or the RTR-Bit

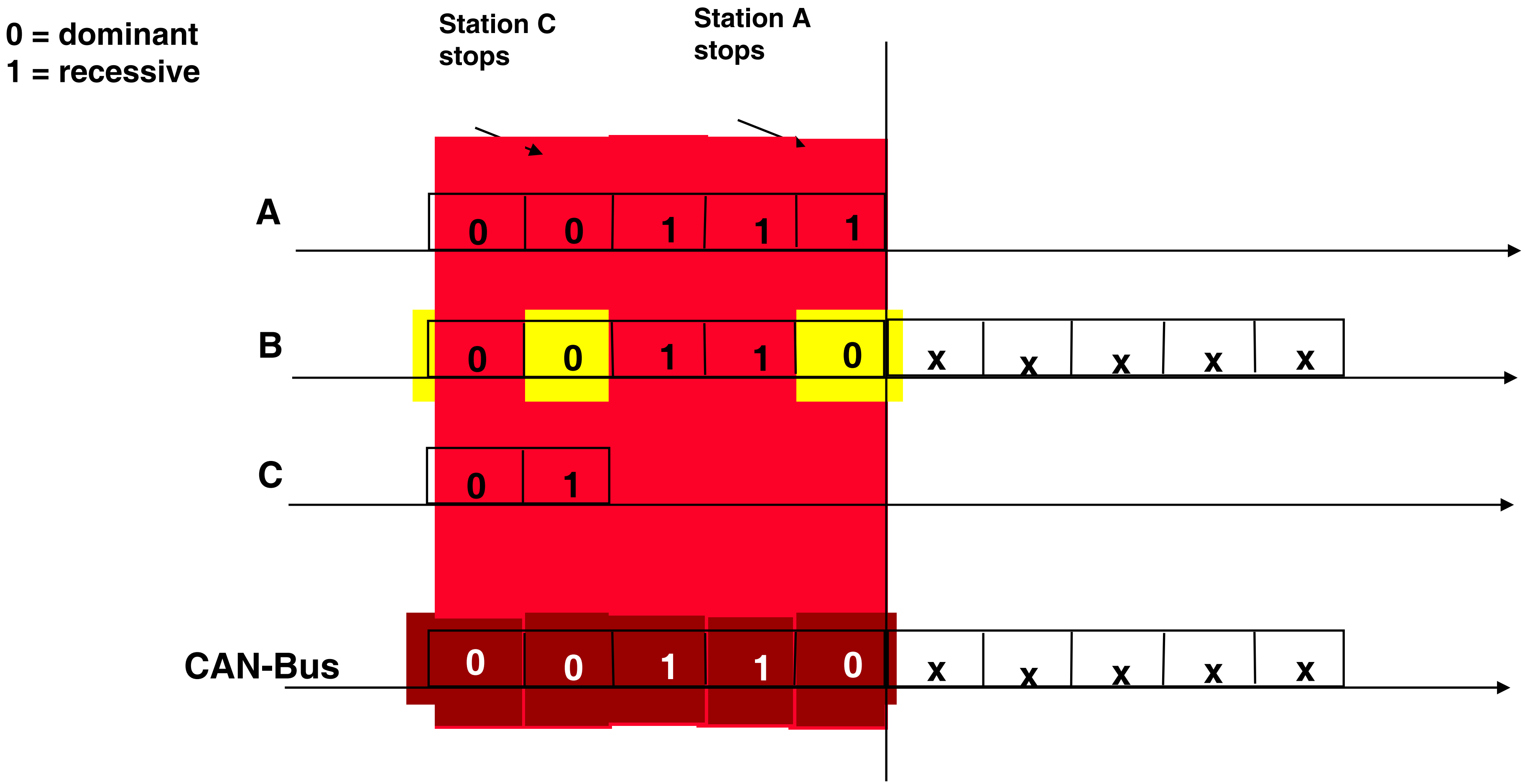
IDE: Identifier Extension. In the SF this is part of the control field, has a dominant value but is not interpreted.
In the EF it is part of the addressing field, has a recessive value and causes the format to be recognized as EF.

SRR: Subsitute Remote Request. Recessive, replaces RTR in the EF for compatibility reasons.

DLC: Data Length Control. 0-8 Byte.

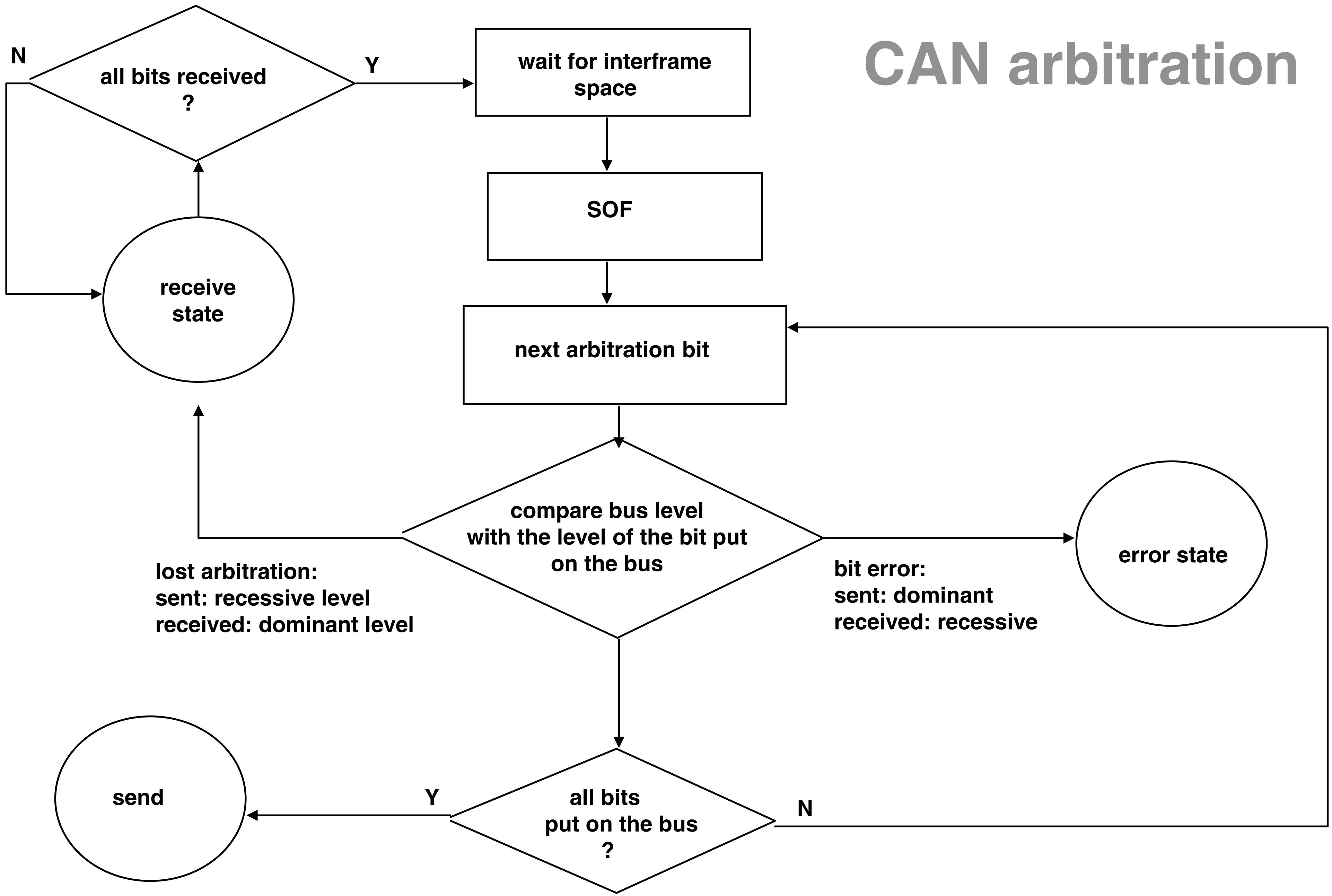
r0, r1: reserved

Arbitration on a CAN-Bus

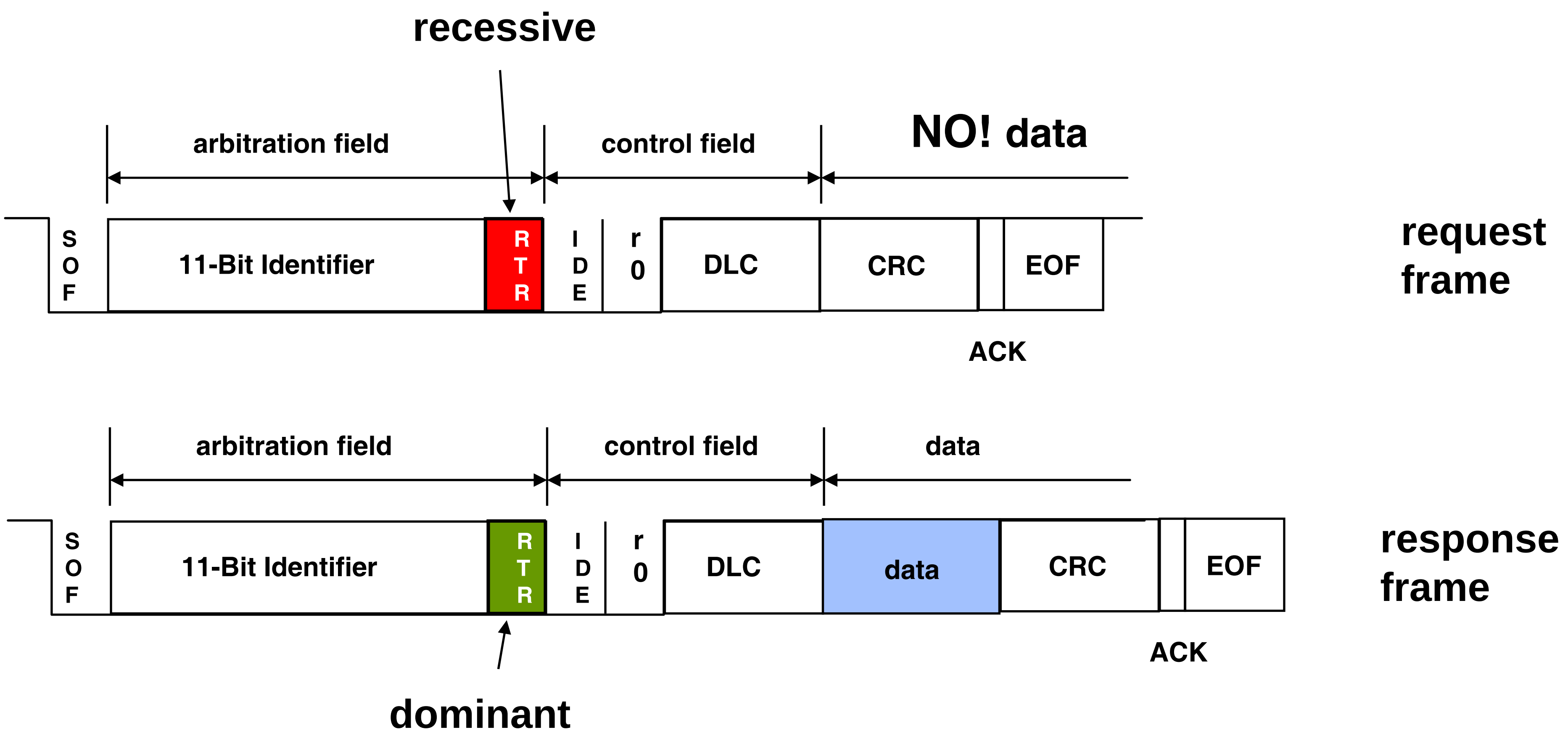


CAN enforces a global priority-based message scheduling

CAN arbitration

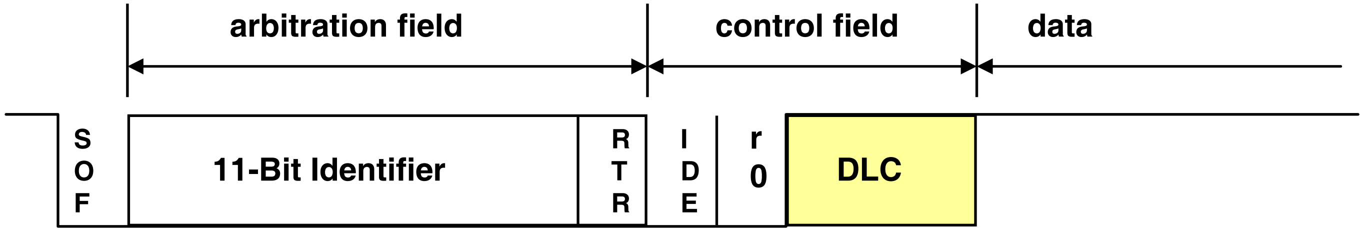


CAN bus Remote Frame

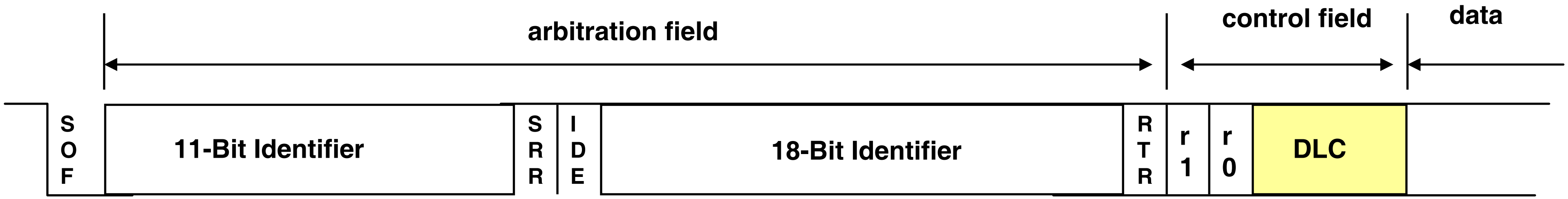


CAN Data Frame

Standard Format SF (compatible to CAN Specification 1.2)



Extended Format EF (CAN Specification 2.0)



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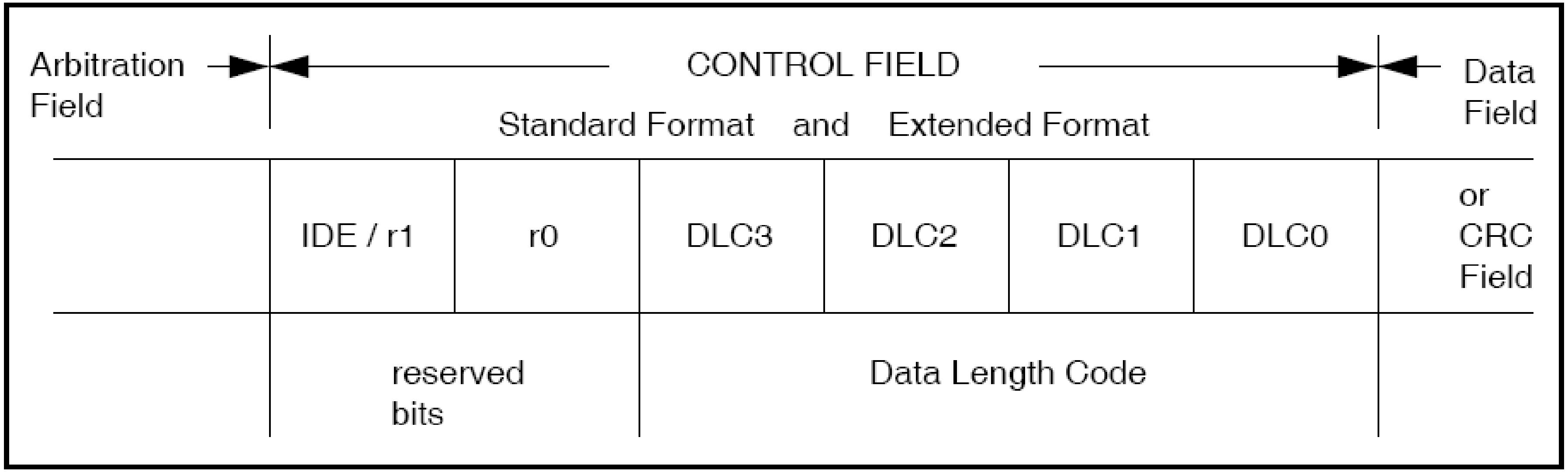
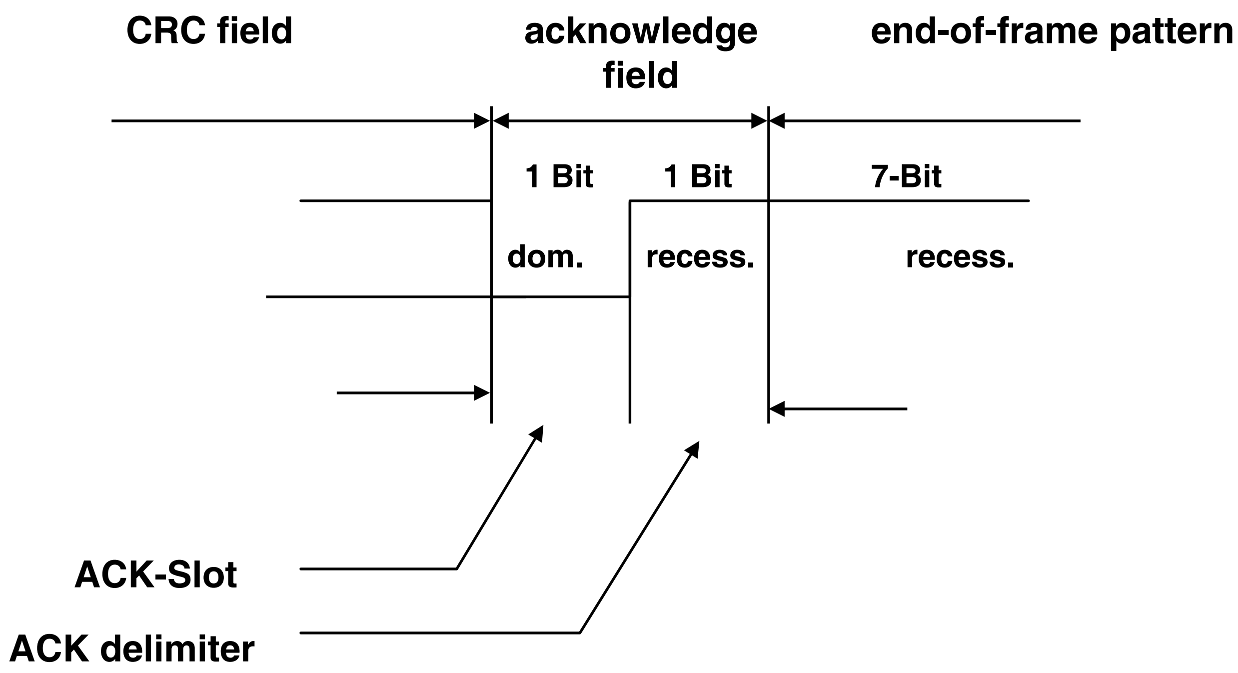
r0, r1:	reserved


Arbitration Field
CONTROL FIELD
Standard Format and Extended Format
Data Field or CRC Field
IDE / r1
r0
DLC3
DLC2
DLC1
DLC0
reserved bits
Data Length Code

Anonymous acknowledgement of a CAN message

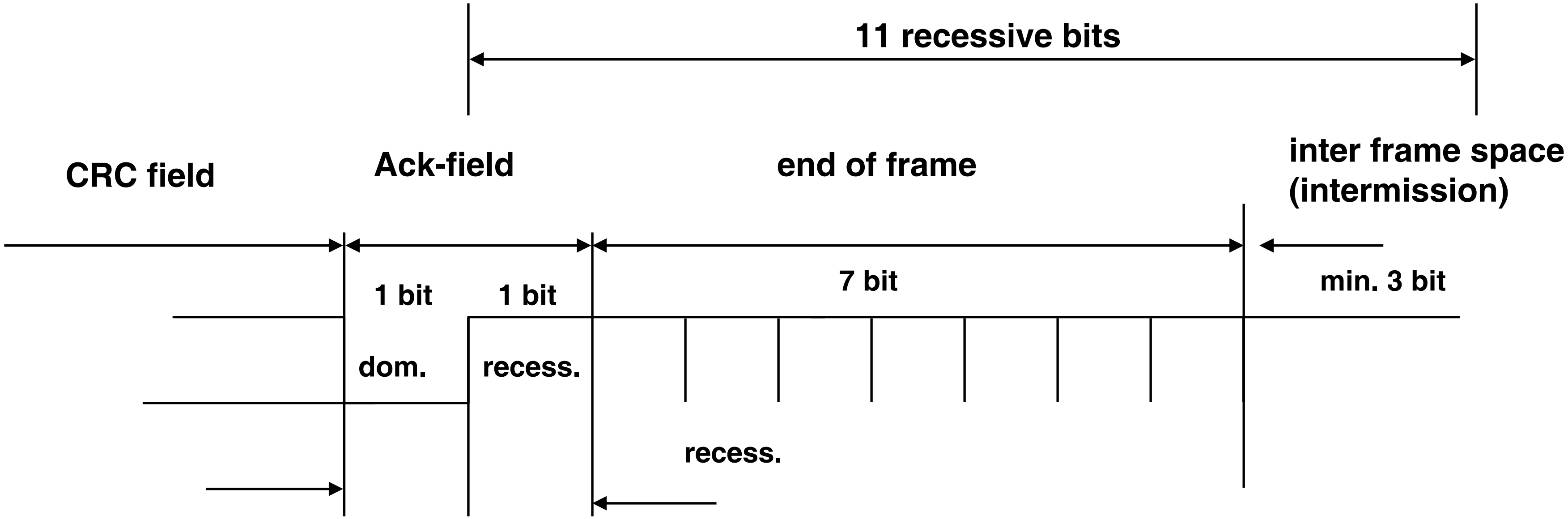


positive anonymous acknowledgement (Broadcast !)

receivers that correctly received a message(a matching CRC sequence) report this in the ack-slot by superscibing the recessive bit of the sender by a dominat bit. The sender switches to a recessive level.

- **Message is acknowledged by a single correct reception on a correct node.**
- **Systemwide data consistency requires additional signalling of local faults.**

Termination sequence of a frame



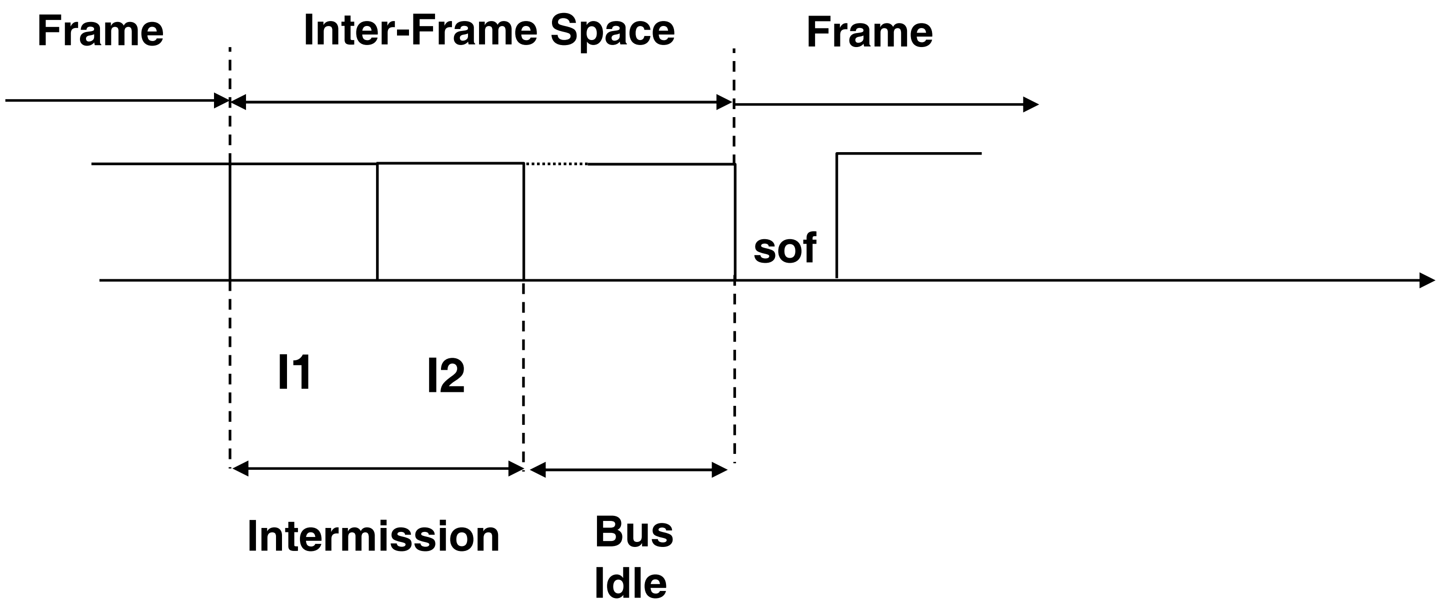
Goals:

1. Detecting AND signalling the error within the actual fame in which it occured
2. Identifying the node which may have caused the error.
3. Creating a systemwide view on the reception state of the message.

Approach: End of frame pattern consisting of 7 recessive bits.

1. Any error detection is signalled by putting a dominant bit on the bus.
2. An out-of-sync node, not being aware of the EOF sequence will signal an error at position "6".

Interframe Space

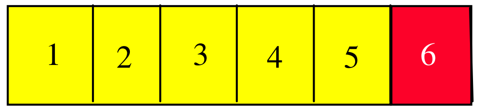


Intermission: no data- or remote Frame may be started

Intermission 1: active overload Frame may be started
Intermission 2: re-active overload frame (after detecting a dominant bit in I1)

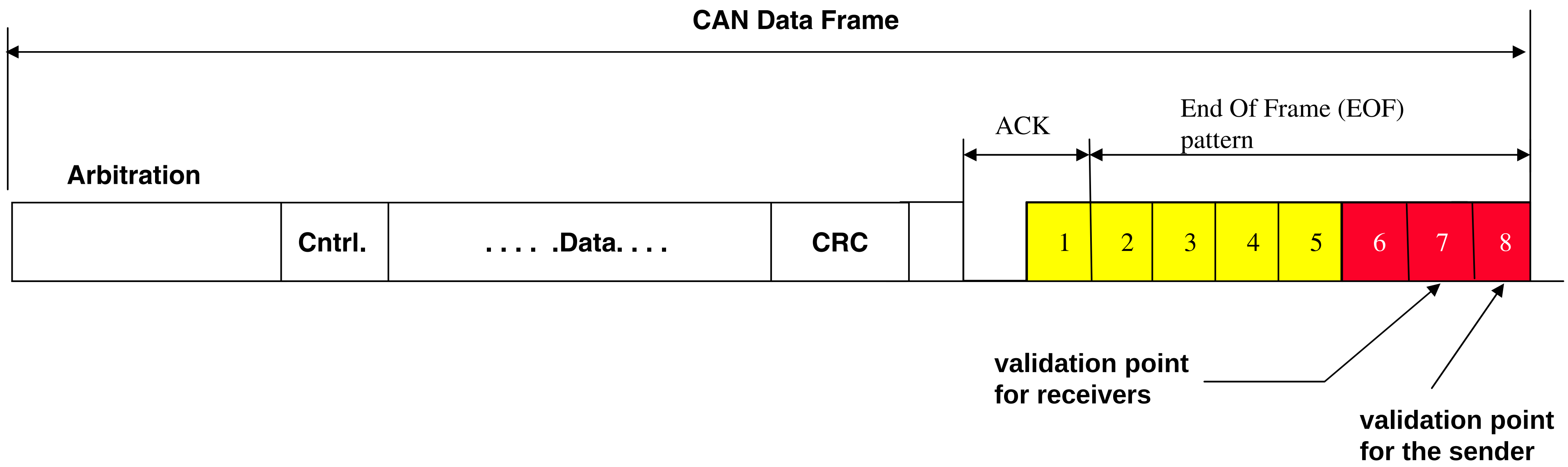
Error Detection and Error Signalling in CAN

Violation of the Bit-Stuffing Rule:
Used for Error Detection and Signalling



Bit-Stuffing enforces the following rule:

A sequence of 5 identical bit levels
is followed by a complementary bit level



Error detection

1.) **Monitoring: Sender compares the bit sent with the bit actually on the bus.**

Type of faults: local sender faults
Error detection: sender based

2.) **Cyclic Redundancy Check:**

Type of faults: 5 arbitrarily distributed faults in the code word, burst error max. length 15.
Error detection: receiver based

3.) **Bitstuffing:**

Type of faults: transient faults, stuck-at-faults in the sender
Error detection: receiver based

4.) **Format control:**

Type of faults: the specified sequence of fields is violated.
Error detection: receiver based

5.) **Acknowledgment:**

Type of faults: no acknowledge
Error detection: sender based, sender assumes local fault.

Risk of undetected errors

Bit monitoring: An error will not be detected if
- the sender is correct and monitoring doesn't detect an error
- all other nodes receive the same bit pattern which is different from that of the sender and contains a non-detectable error.

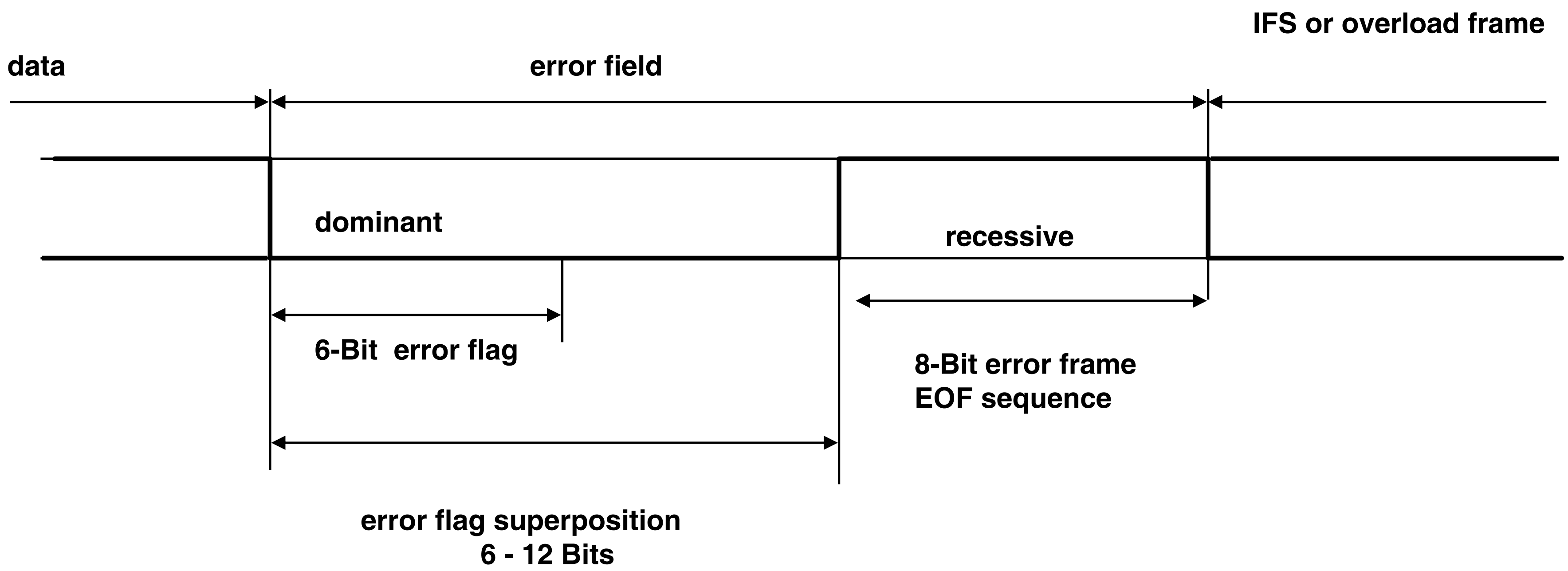
CRC: difference between fame sent and received is a multiple of the generator polynome.

Frame errors: the frame is shortened or additional bits are added. Ath the same time a corect end-of-frame sequence is generated.

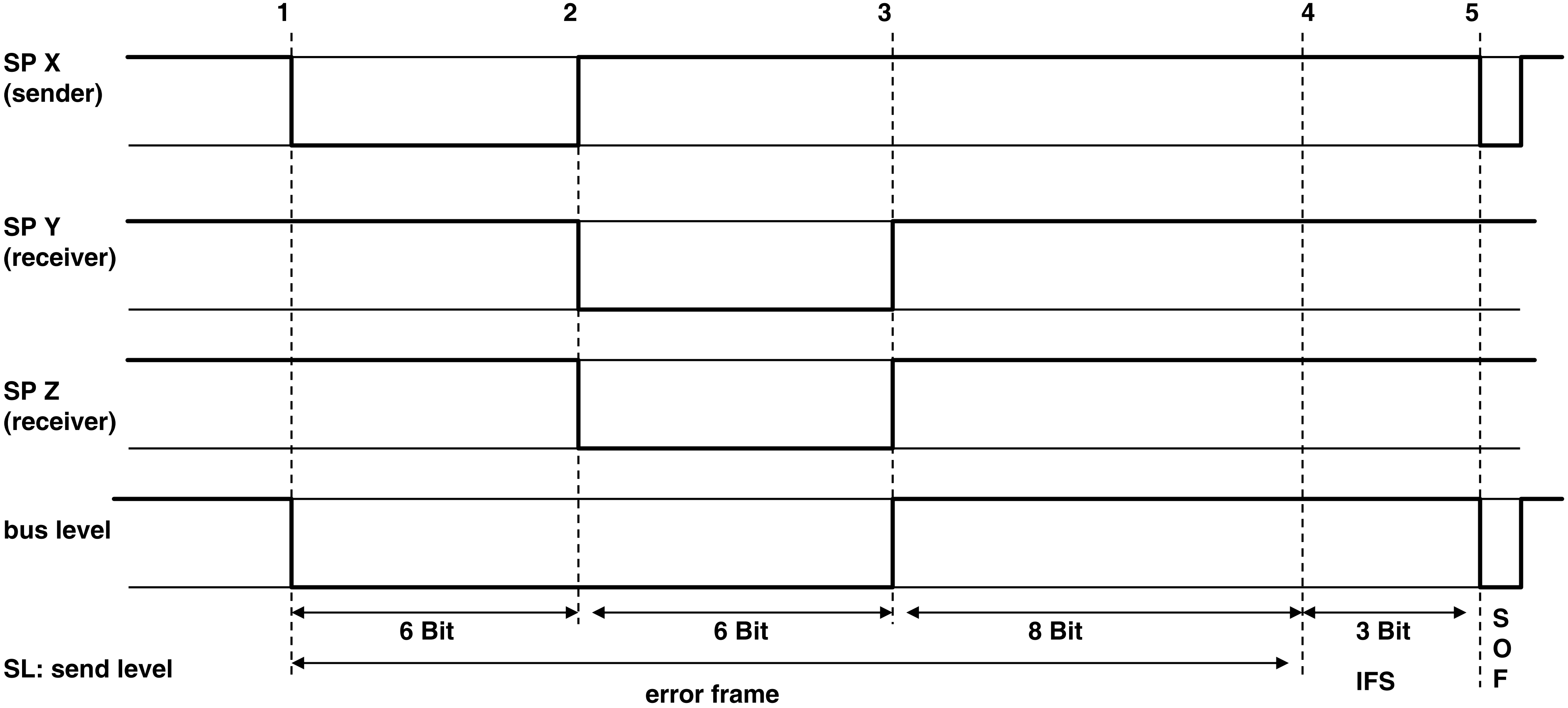
Unruh, Mathony und Kaiser:"Error Detection Analysis of Automotive Communication Protocols", SAE International Congress, Nr. 900699, Detroit, USA, 1990

Scenario:
nodes: 10, Bit error rate: $2 \cdot 10^{-2}$, message error rate: 10^{-3}
risk of undetected errors: $4{,}7 \cdot 10^{-14}$
When the number of nodes increase, the probability of undetected errors decreases.

CAN error frame

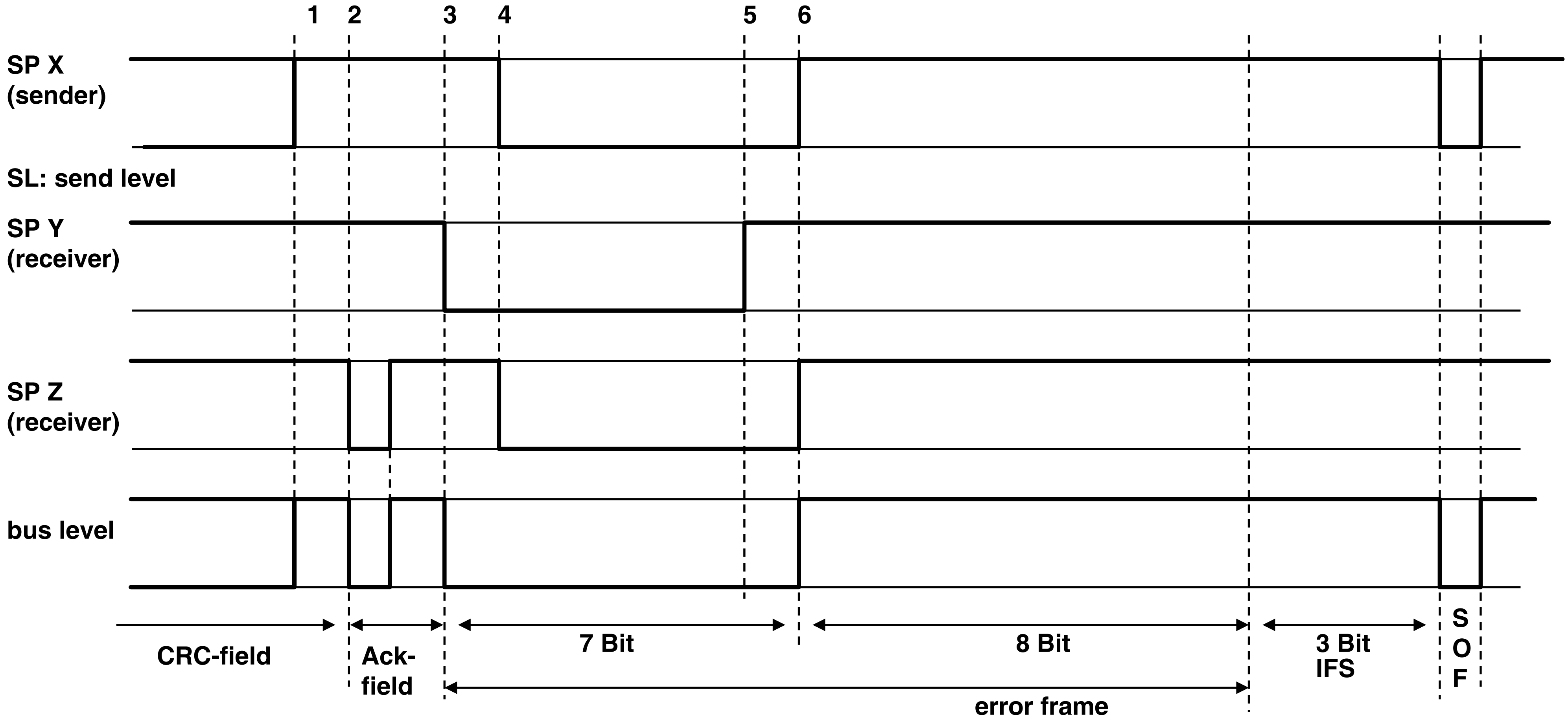


Error frame resulting from a sender fault



time to re-transmit a faulty message frame: min. error recovery time: 23 bit times

Error frame resulting from a receiver fault



time to re-transmit: min. error recovery time: 20 bit times

Enforcing fault confinement and a “Fail Silent” behaviour

Problem: Faulty component may block the entire message transfer on the CAN-Bus.

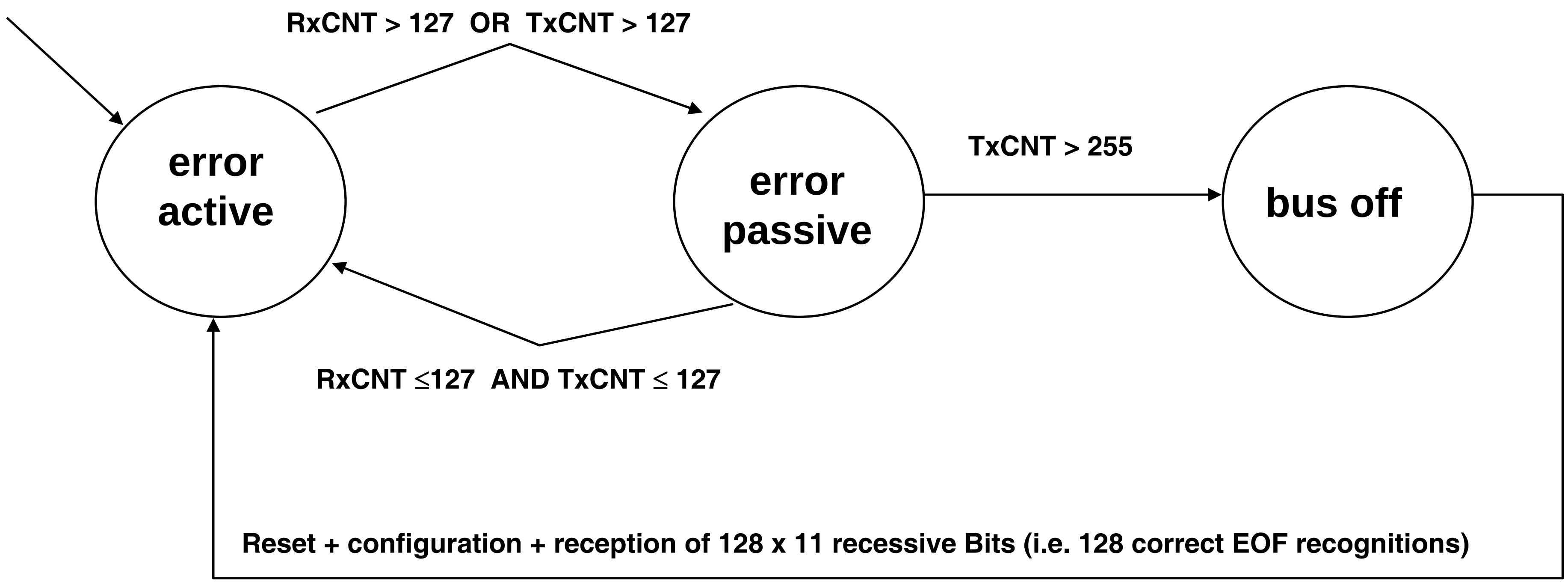
Assumption:
1. A faulty node detects the error first.
2. frequently being the first which detects an error --> local fault in the node

approach: error counter for receive and transmit errors. If error was first detected by the node, the counter is increased by 8-9.

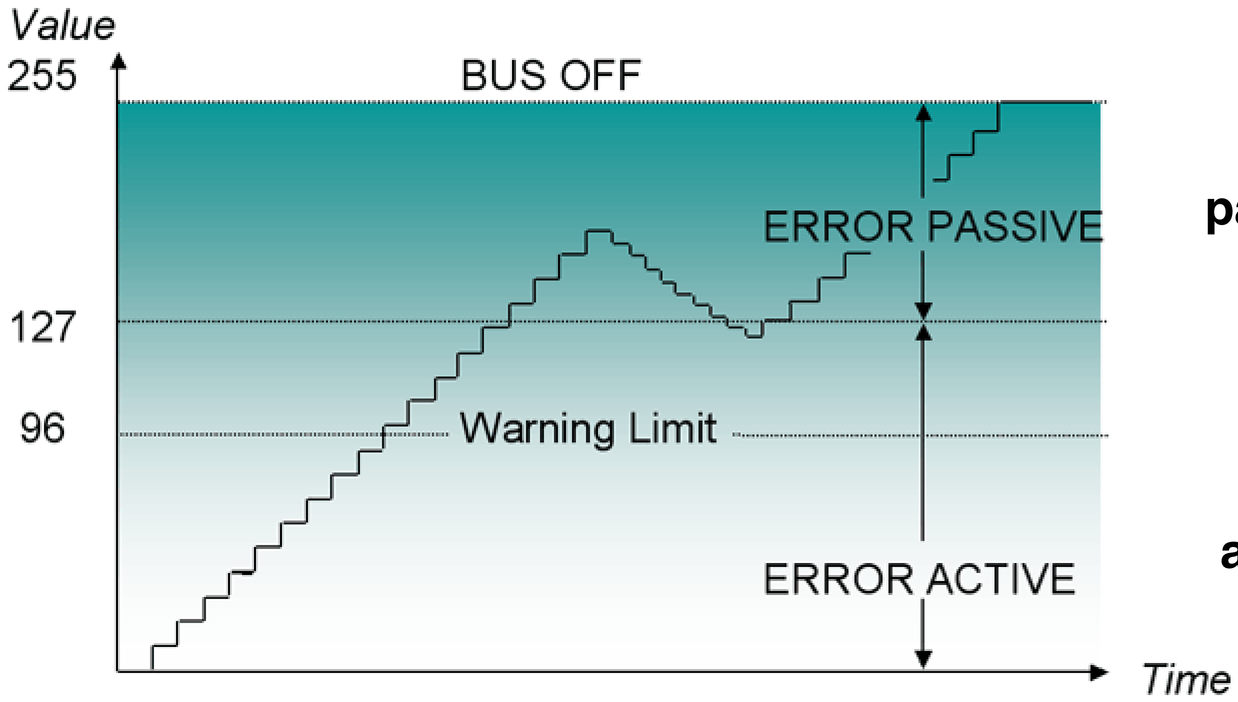
Enforcing fault confinement and a “Fail Silent” behaviour

States of a CAN node:
- **error active**
- **error passive**
- **bus off**

RxCNT: Value of the receive counter
TxCNT: Value of the transmit counter



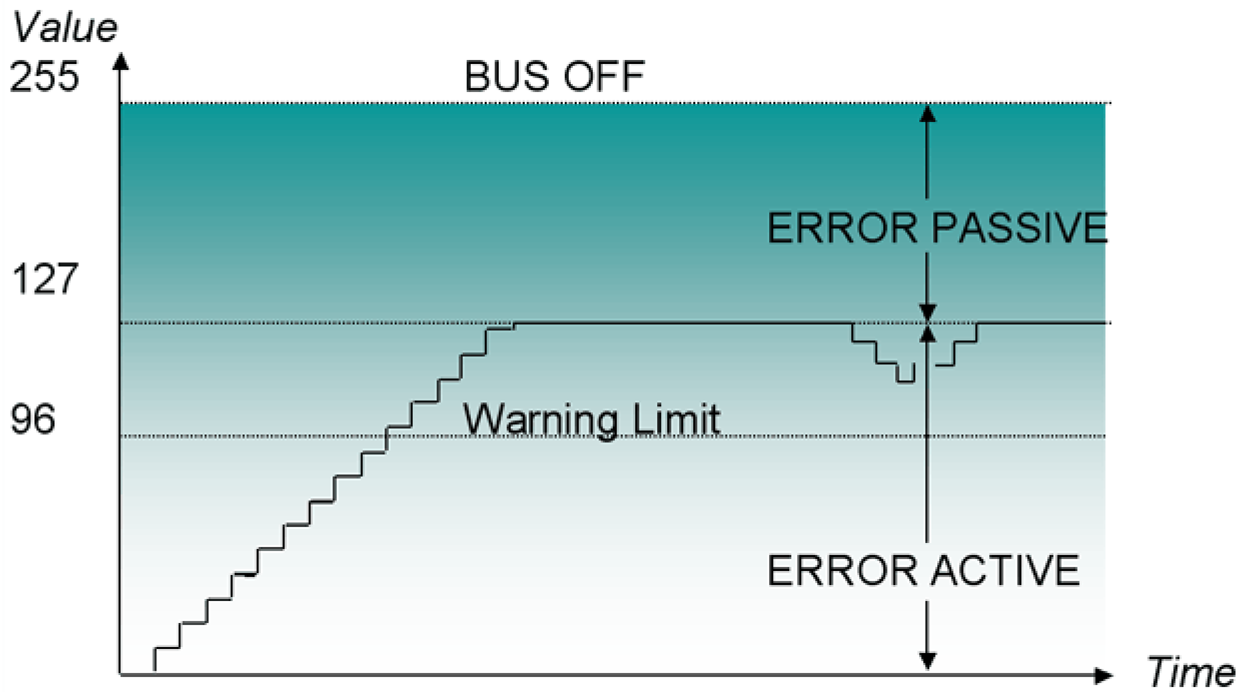
CAN bus Error Handling - Transmit Error Counter



passive error frame

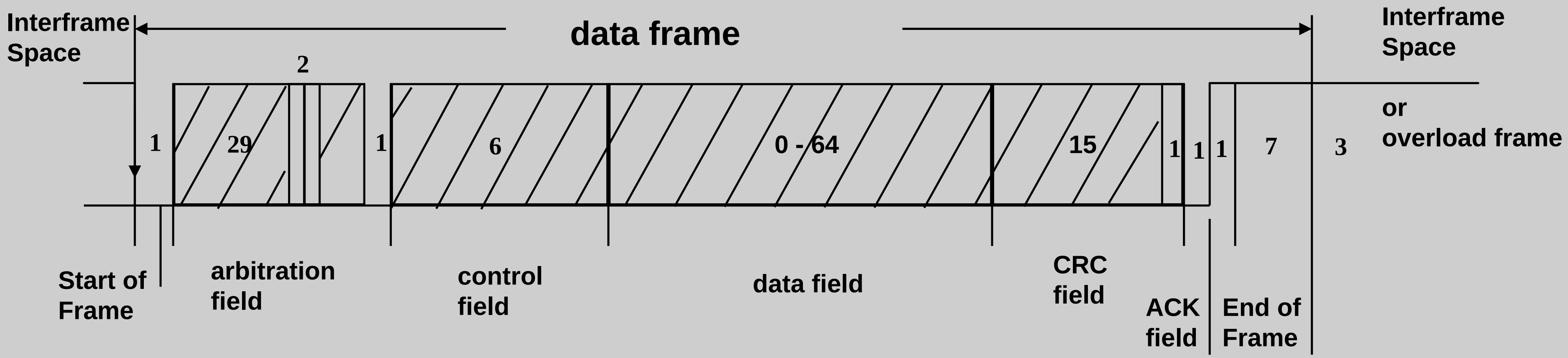
active error frame

CAN bus Error Handling - Receive Error Counter



Analysis of CAN inaccessibility

CAN Data Frame



longest possible message:

Format-Overhead:	67 bit times
Data:	64 bit times
Bitstuffing (max):	23 bit times
total:	154 bit times

CAN Inaccessibility Times*

Data Rate 1 Mbps , Standard Format

Scenario	t_{inacc} (µs)	
Bit Errors	155.0	← worst case single
Bit Stuffing Errors	145.0	
CRC Errors	148.0	
Form Errors	154.0	
Ack. Errors	147.0	
Overload Errors	40.0	
Reactive Overload Errors	23.0	
Overload Form Errors	60.0	
Transmitter Failure	2480.0	← worst case multiple
Receiver Failure	2325.0	

P. Verissimo, J. Ruffino, L. Ming:" How hard is hard real-time communication on field-busses?"

Predictability of various Networks*

Worst Case Times of Inaccessibility*	t_{inacc} (ms)	
ISO 8002/4 Token Bus (5 Mbps)	139.99	Token-based Protocols
ISO 8002/5 Token Ring (4 Mbps)	28278.30	
ISO 9314 FDDI (100 Mbps)	9457.33	
Profibus (500 kbps)	74.80	
CSMA/CD	unbounded	CSMA Protocols
CSMA/CA	stochastic	
CAN-Bus (1Mbps)	2.48	

The worst-case-delay of the Timed-Token-Protocol is 2•TTRT (Target Token Rotating Time)**

* P. Verissimo, J. Ruffino, L. Ming:" How hard is hard real-time communication on field-busses?"
** J.N. Ulm: "A Timed Token Ring Local Area Network and its Performance Characteristics"
R.M. Grow: " A Timed Token Protocol for local Area Networks"

CAN-Bus Properties (summary)

- Event-triggered communication with low latency
- Priority-based arbitration with collision resolution for guaranteed throughput
- error handling:
  - anonymous positive acknowledge
  - negative ack. in case of an error (systemwide messaging)
  - identification of faulty nodes
  - immediate synchronisation and retratnsmission
- content-based addressing with a high flexibilitx (system elasticity)

Elasticity Mechanisms

Anonymous Communication

Every message is broadcasted to every station

Acceptance filtering on the receiver side

The arbitration field is used to identify a message, not a source or destination address

Content based message tagging

Reliability of message transfer

Decentralized mechanism for consistent error handling

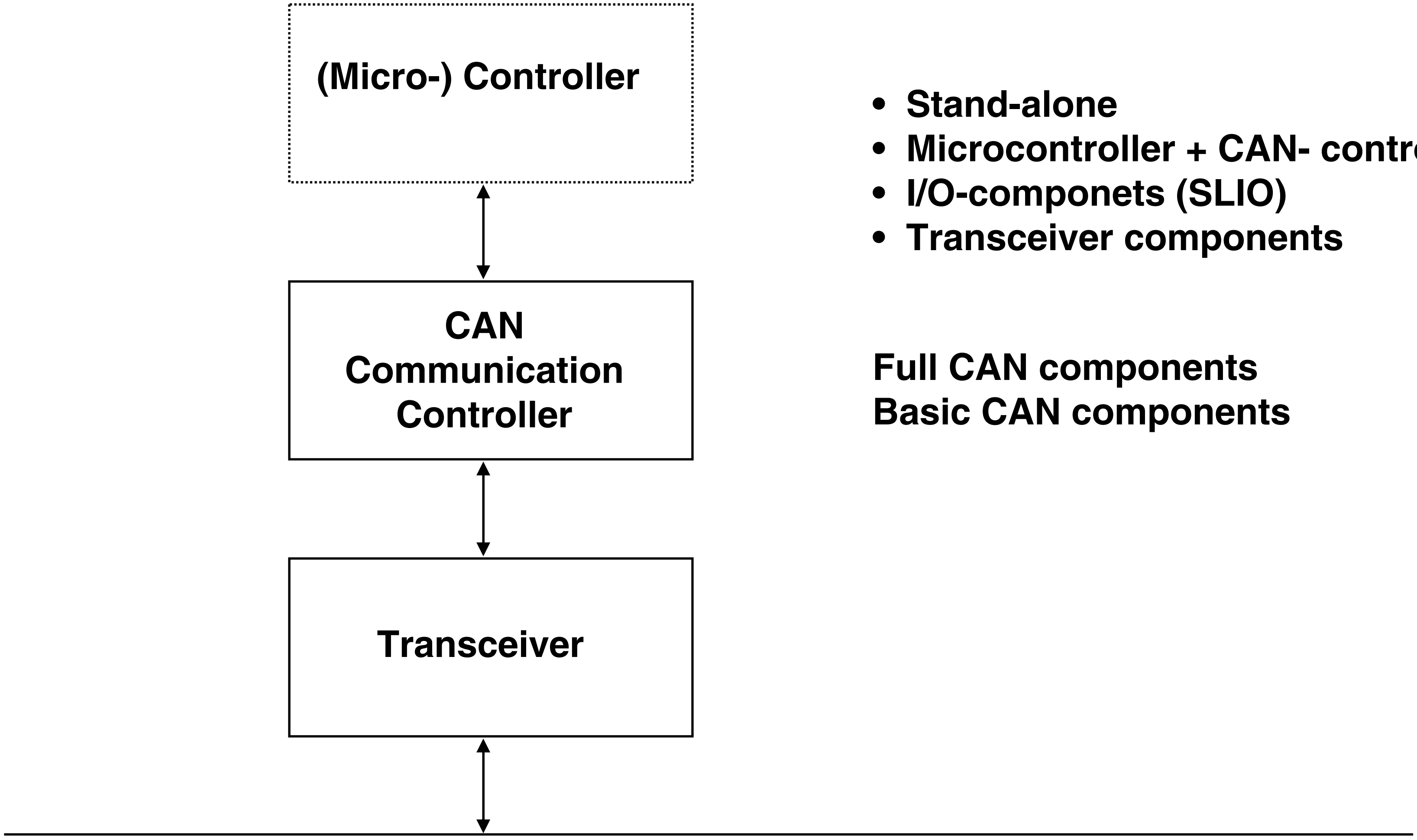
➡ System consistency

All nodes have the same view about the status of a message

➡ Fault Confinement

Preventing contention of network due to faulty network controller

CAN components



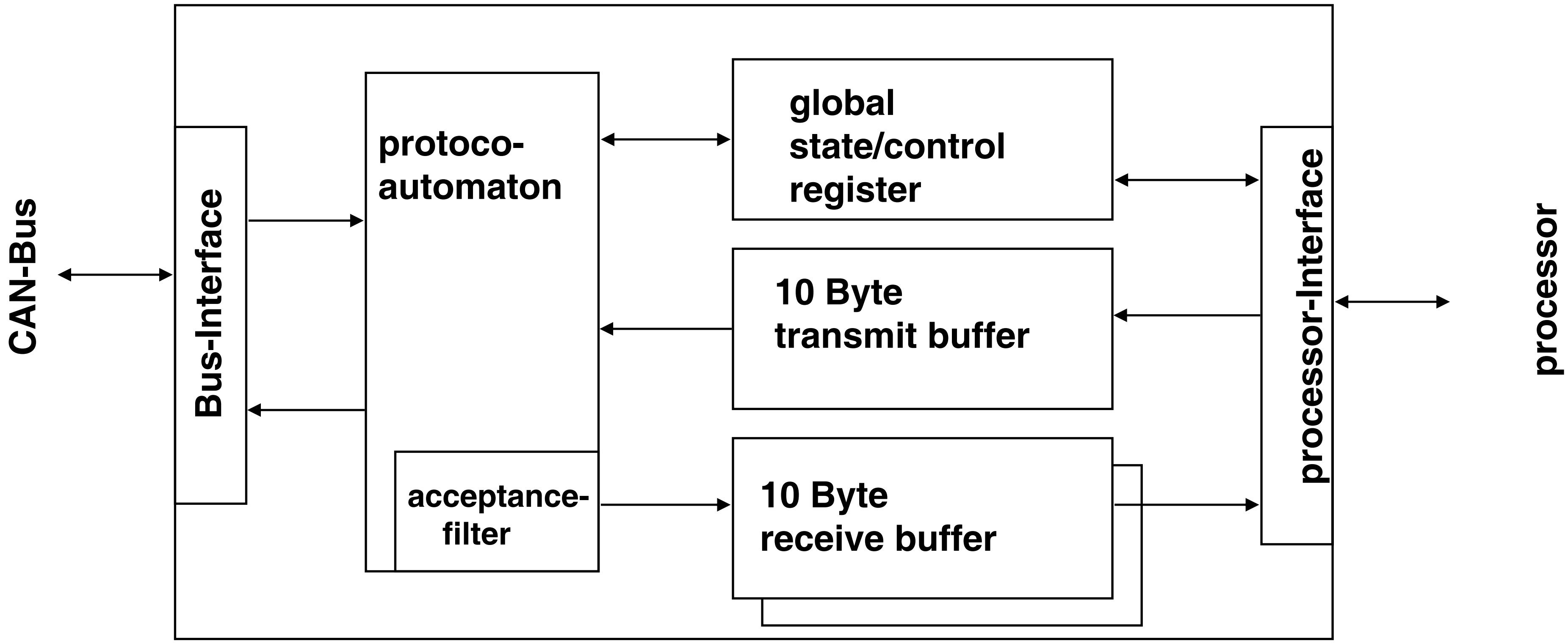
- Stand-alone
- Microcontroller + CAN- controller
- I/O-componets (SLIO)
- Transceiver components

Full CAN components
Basic CAN components

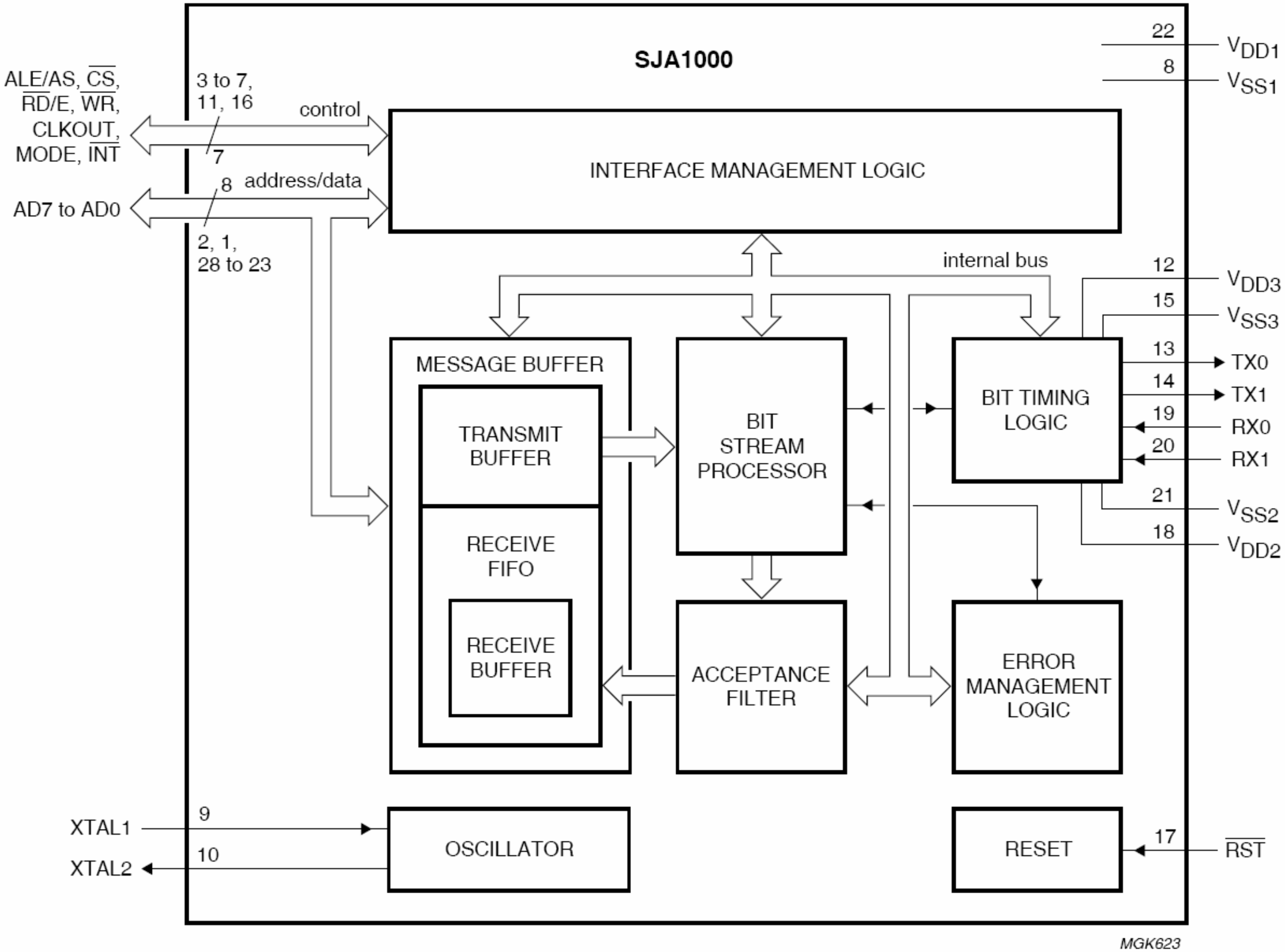
Tasks of a CAN Controller

- bus arbitration
- assembling and de-assembling CAN frames
- generating and checking of the CRC
- error detection and signalling
- inserting and deleting stuff bits
- generating and testing the acknowledge pattern
- synchronizing the bit stream

Basic CAN Controller



SJA1000 (Philips)



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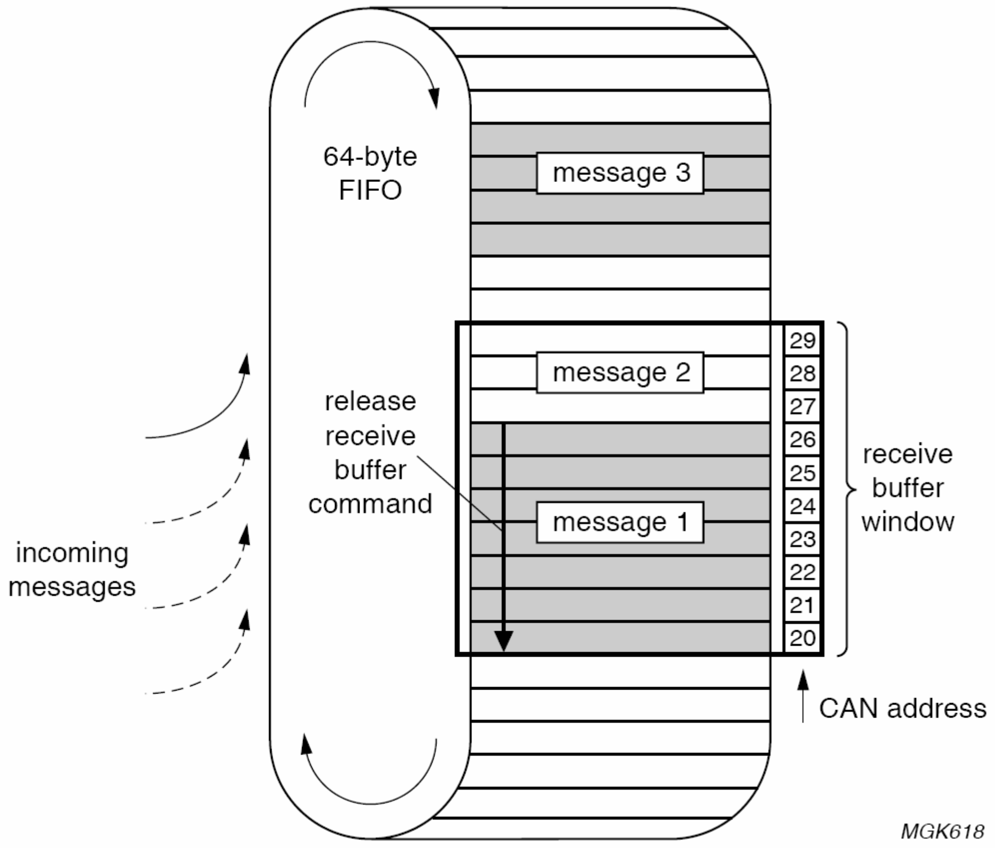


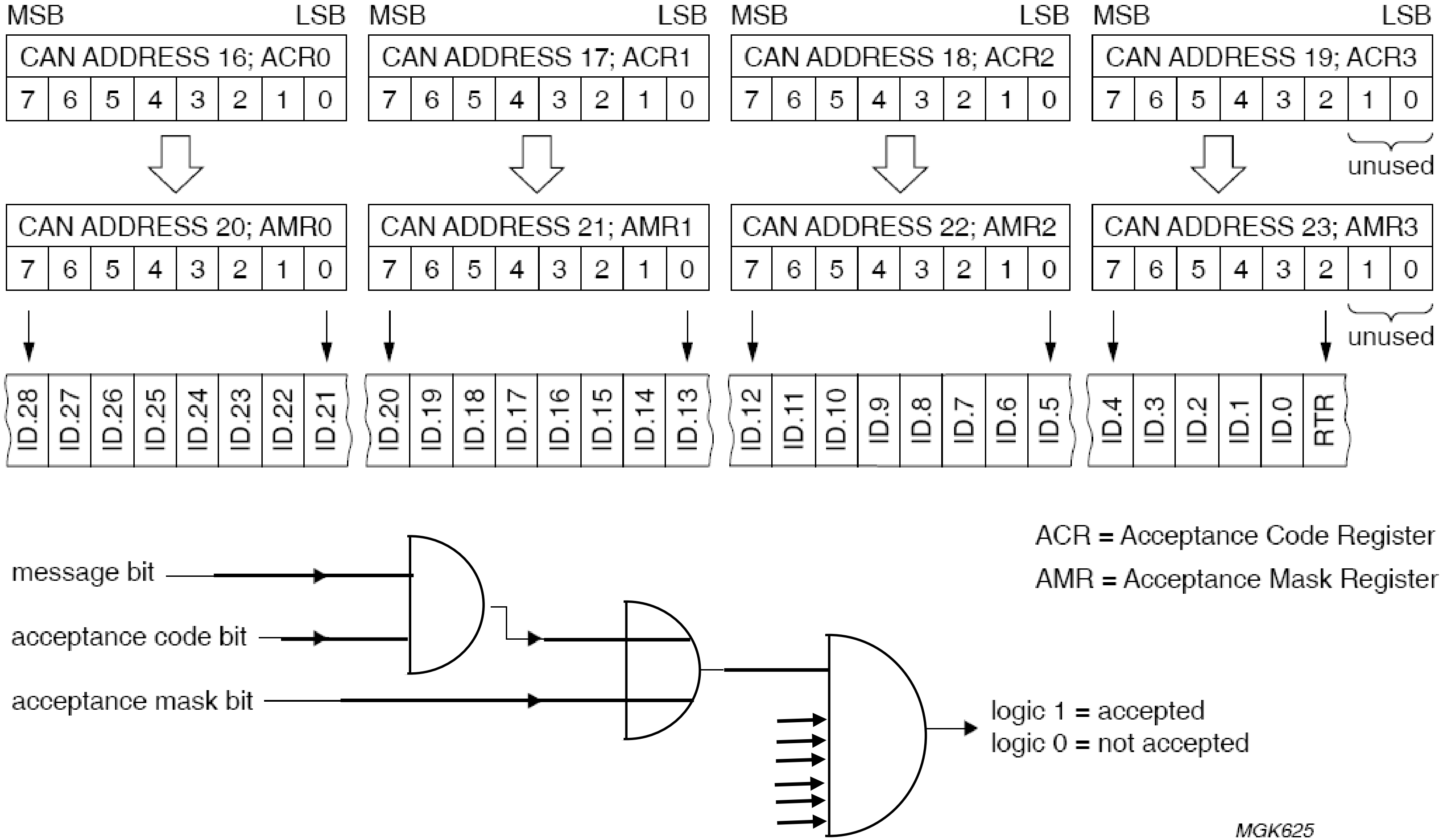
acceptance filtering

message register	1	1	0	1	1	0	1	1	0	1	0	0	0	0	1	1	0	1	0	0
filter mask	x	1	x	x	x	x	1	1	0	1	0	0	0	0	1	1	x	x	x	x

The number of message registers, configuration options and filters depend on the respective communication controller.

SJA1000 (Philips)

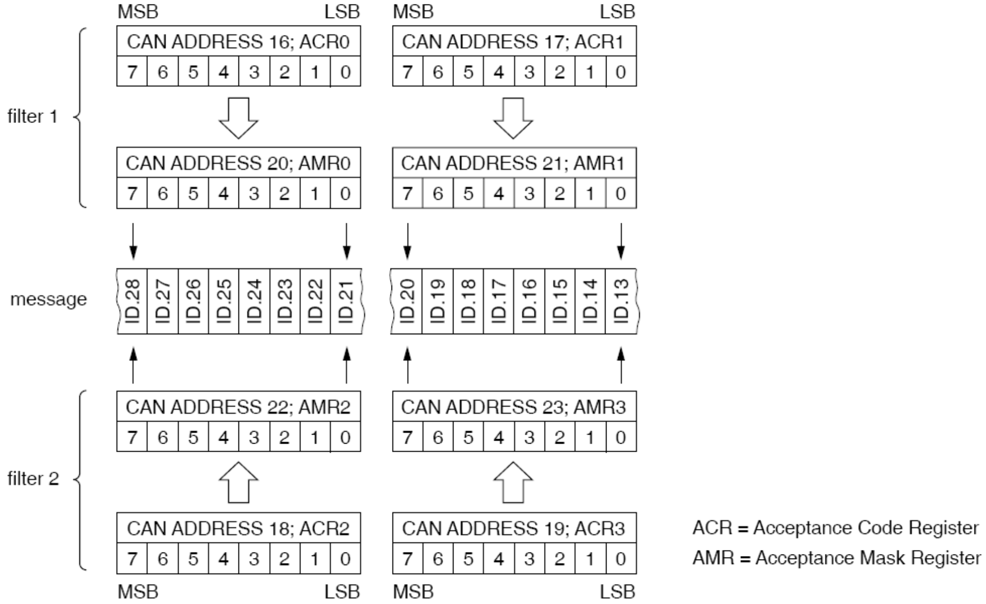
single mask option

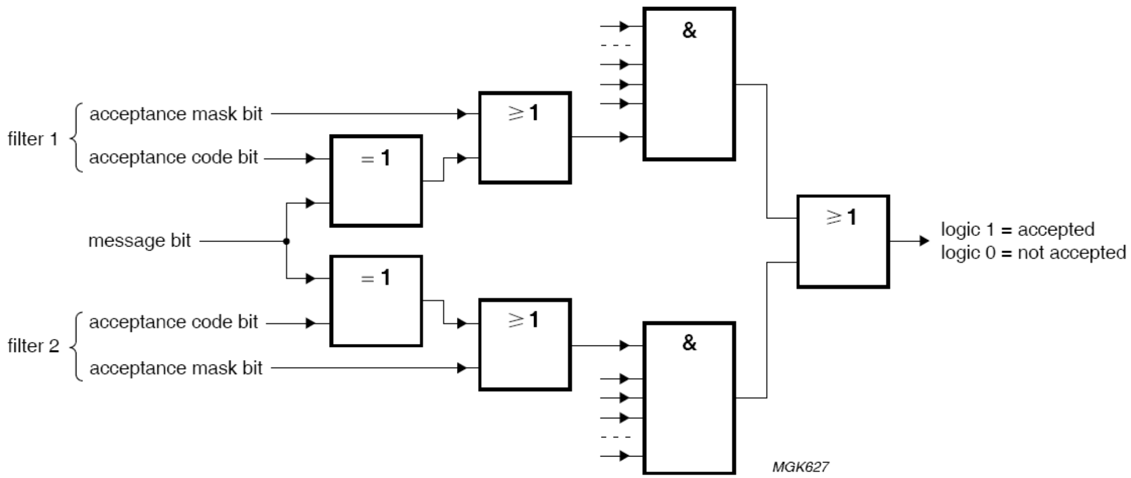


ACR: defines the pattern of CAN message IDs which are accepted.
AMR: defines a mask of "don't care" positions.

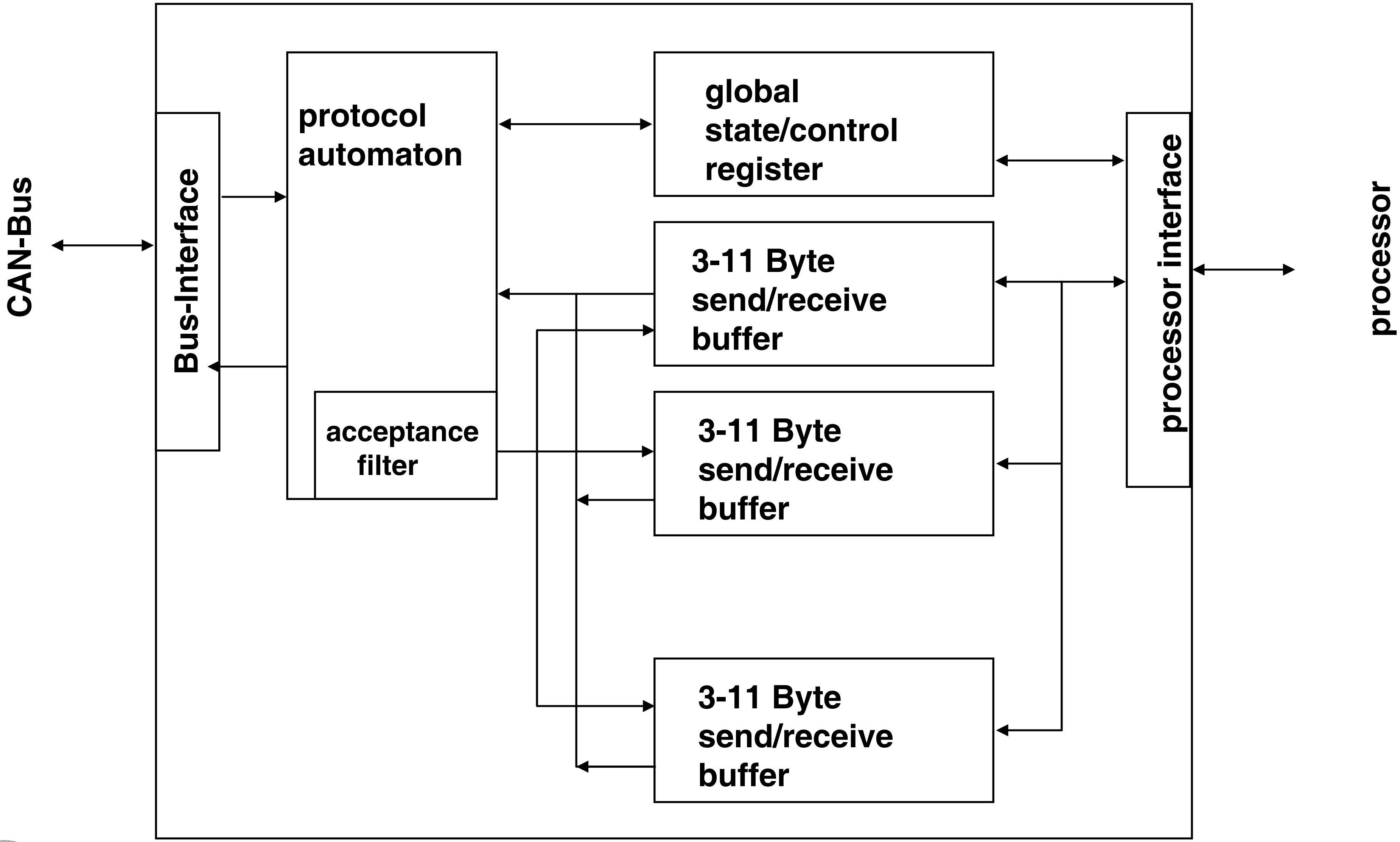
SJA1000 (Philips)

dual mask option



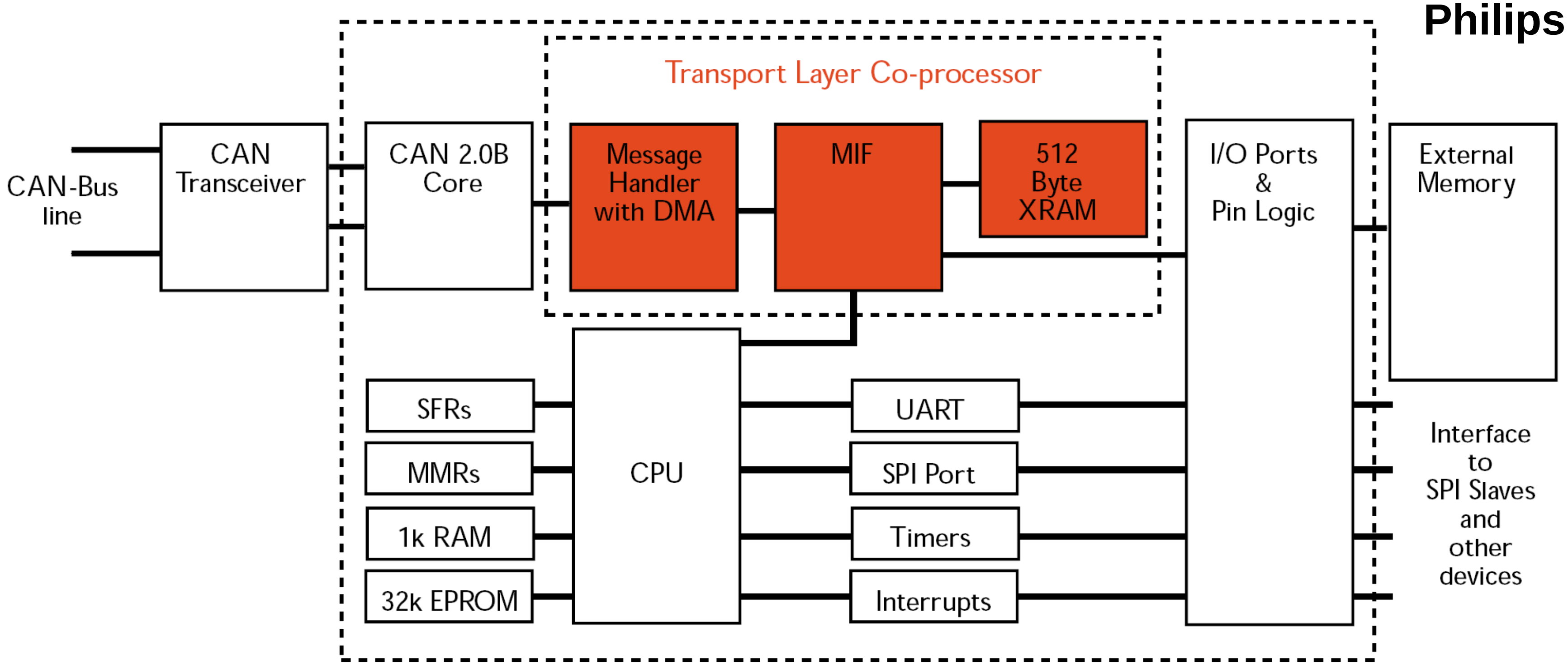


Full CAN controller



XA-C3: Support for higher layer protocols

Philips



XA-C3 supports:

- **Full CAN with 32 message objects**
- **Extended Buffering of received messages**
- **Pre-arbitration of local transmit-queue**
- **Fragmentation protocols according to various CAN Higher Level Protocols**

Peter Hank: XA-C3 Supports CAN Higher Layer Protocols, Systems Laboratory Hamburg

Pre-arbitration in the local transmit queue

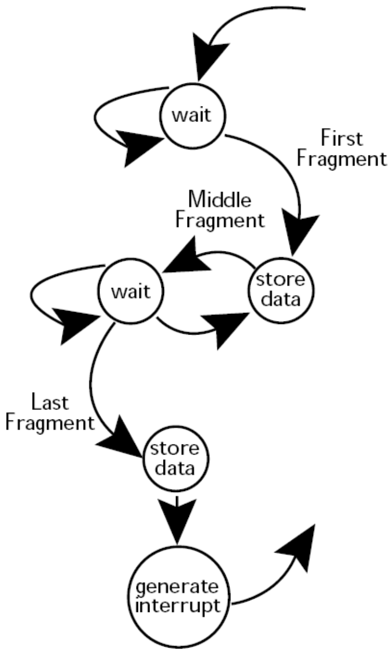
Arbitration by message object

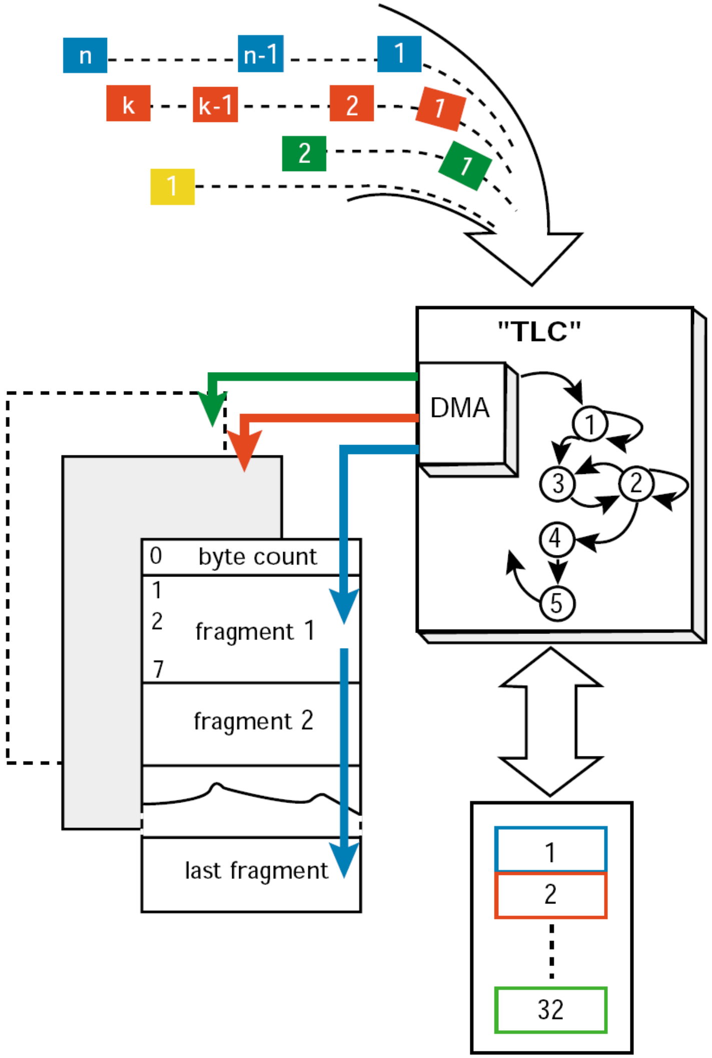
5	0010....
4	0011....
3	1010....
2	1100....
1	0101...

Arbitration by priority of message object

5	1100....
4	1010....
3	0101....
2	0011....
1	0010....

Fragmentation Support





- Automatic reassembling of long messages.

- Supports CanOpen, Devicenet and OSEK standards

What CAN can't

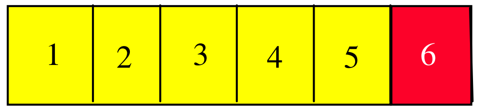
- All-or-nothing property under all single (crash/omission) fault conditions

- Temporal guarantees for message transmissions

- Consistent order of messages

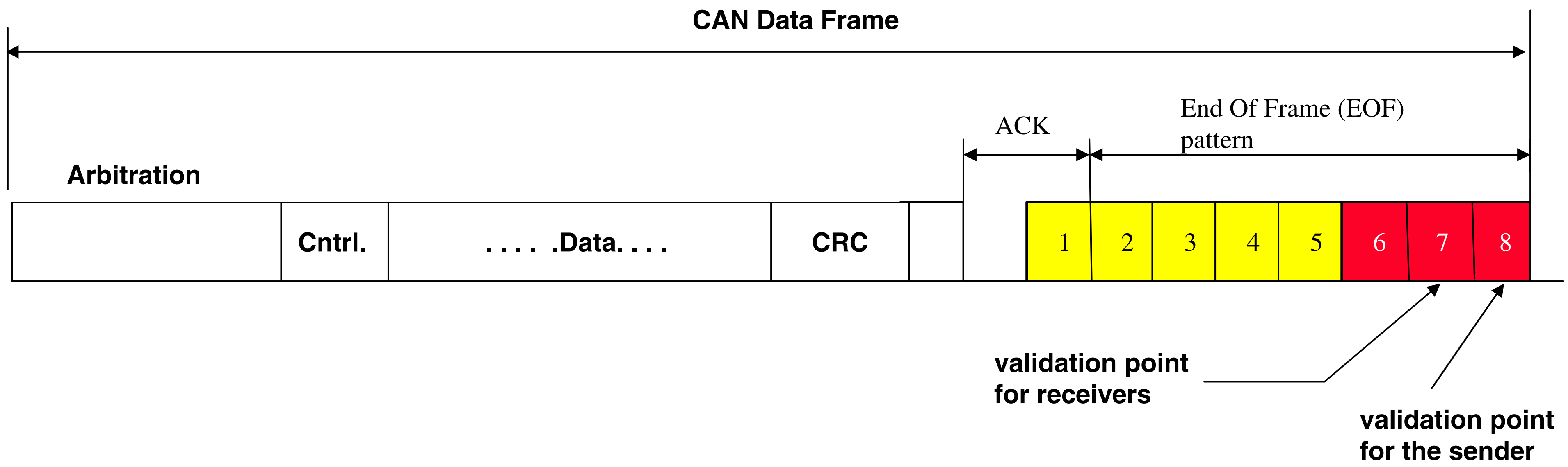
Error Detection and Error Signalling in CAN
The Case for Inconsistencies

Violation of the Bit-Stuffing Rule:
Used for Error Detection and Signalling



Bit-Stuffing enforces the following rule:

A sequence of 5 identical bit levels
is followed by a complementary bit level



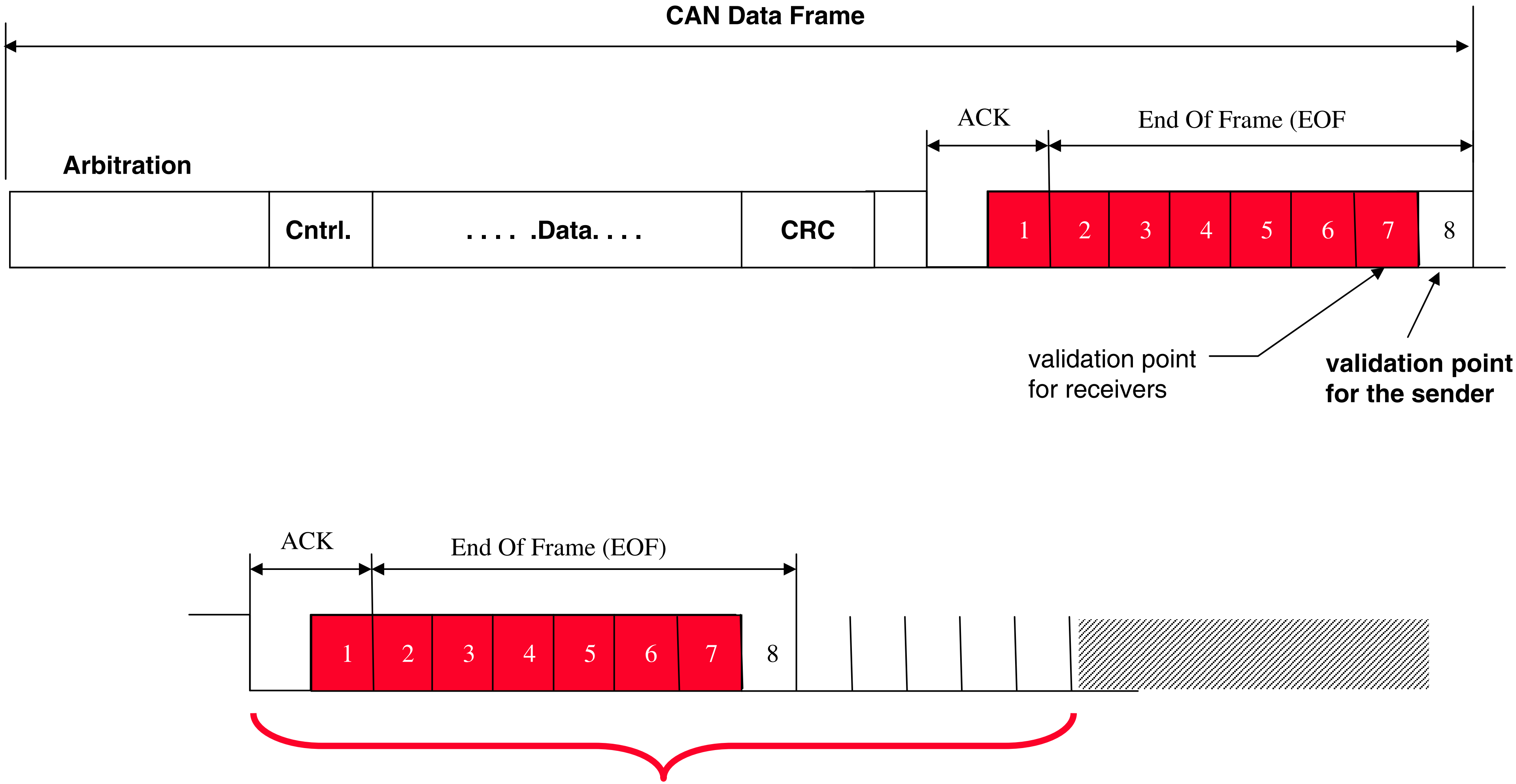
Consequences from the validation protocol

J. Rufino, P. Veríssimo, C. Almeida , L. Rodrigues: „Fault-Tolerant Broadcasts in CAN“, *Proc. FTCS-28, Munich, Germany, June 1998.*

J. Kaiser, Mohammad Ali Livani: “Achieving Fault-Tolerant Ordered Broadcasts in CAN” *Proc. of the 3rd European Dependable Computing Conference, (EDCC-3), Prague, Sept. 1999*

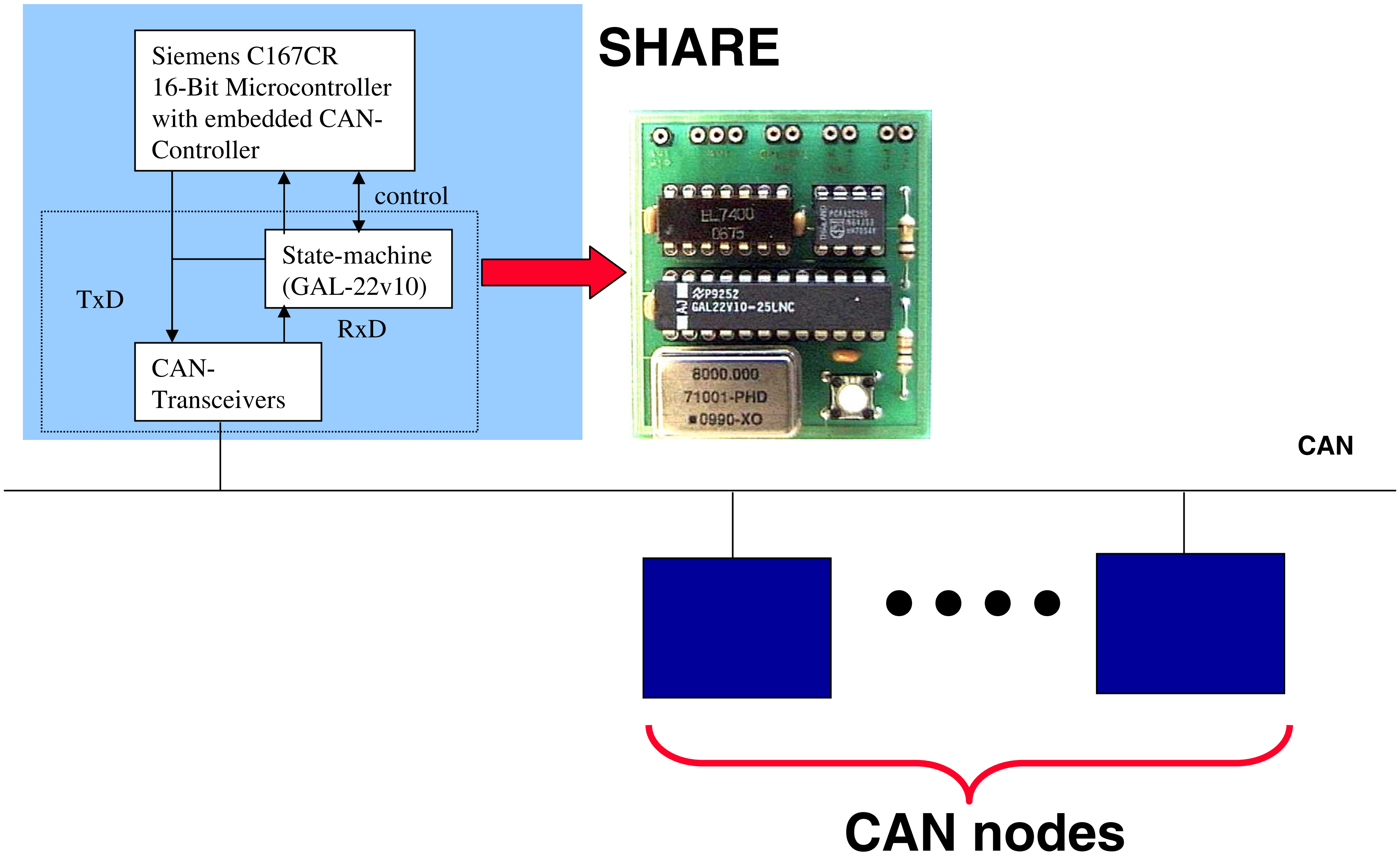
- inkonsistent message duplicates
- inkonsistente omissions
- (potentially) unbounded delays

The Case for SHARE: Inconsistent Omissions

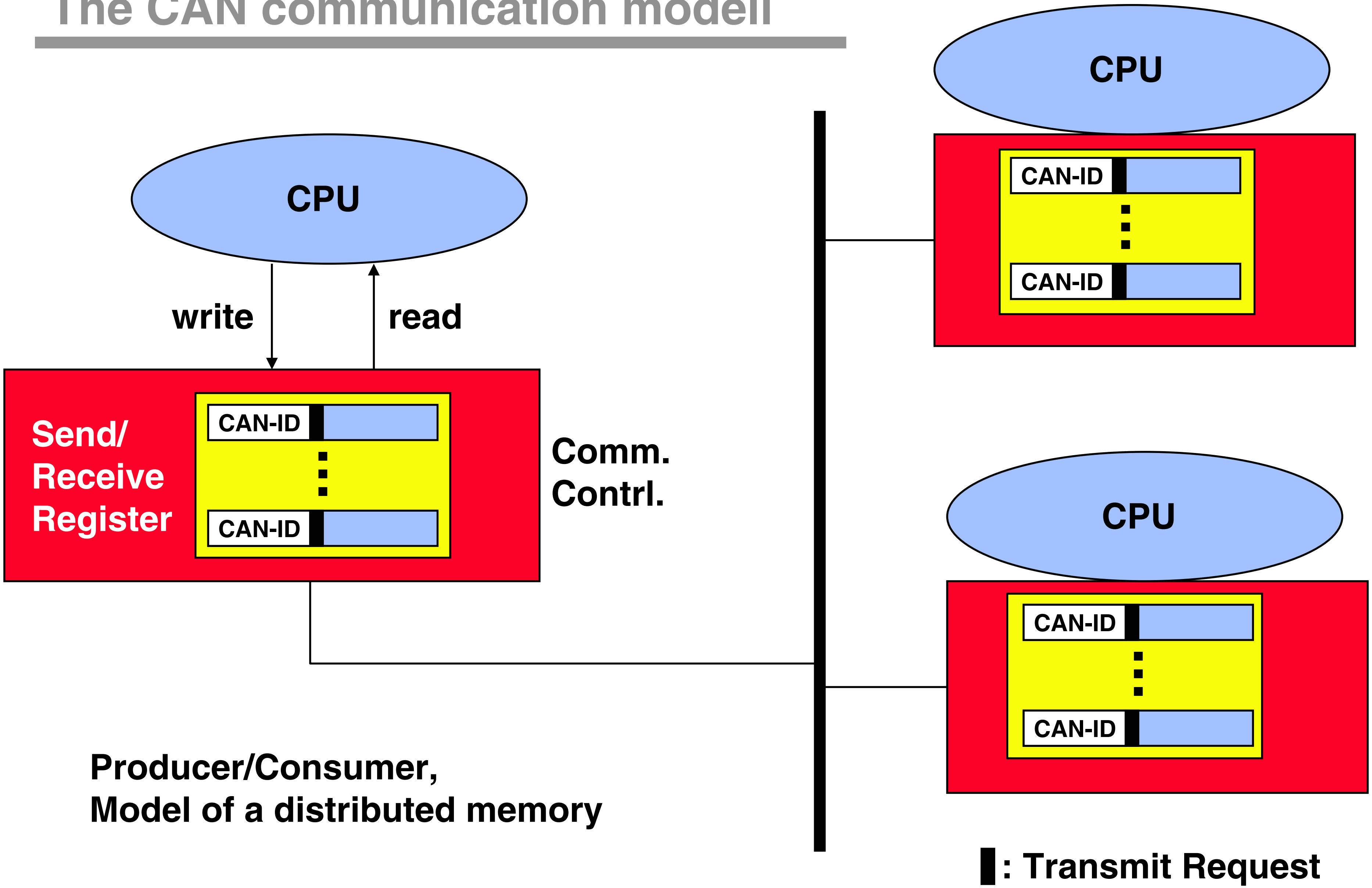


unique pattern : 1 dominant, 7 recessive, 6 dominant !

The Architecture of SHARE

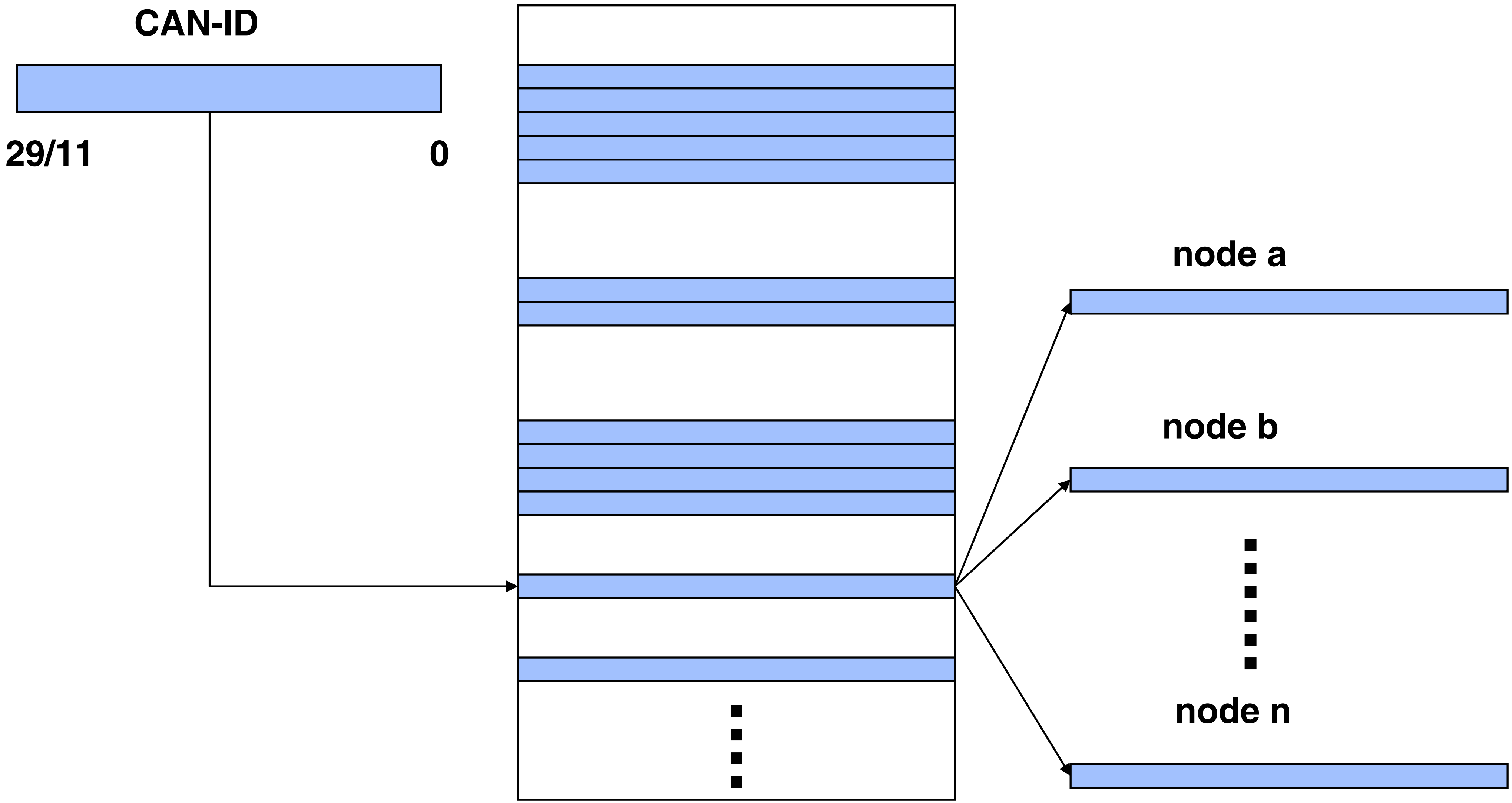


The CAN communication modell

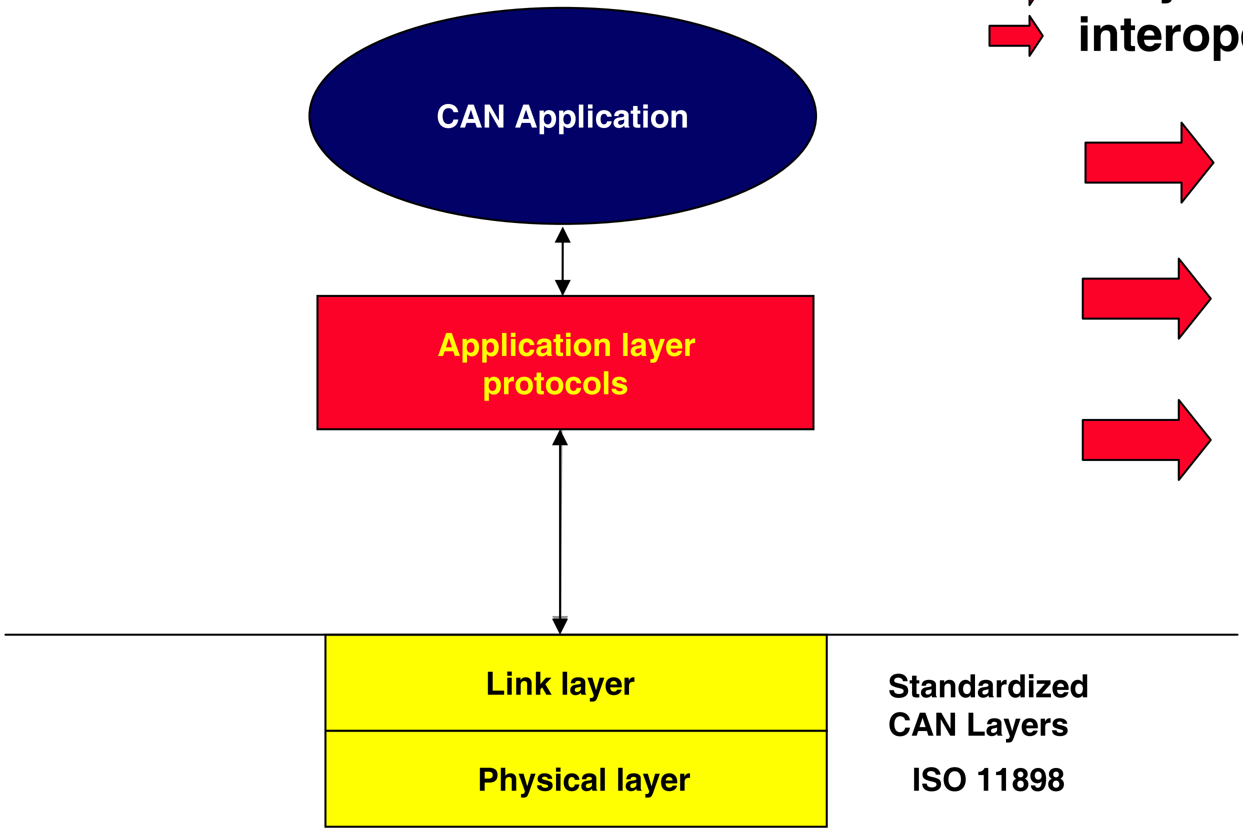


Producer/Consumer,
Model of a distributed memory

The CAN communication modell



Application Level Protocols



Goals:

- easy to use programming interfaces
- interoperability in an open network

Data/communication model

Real-time issues

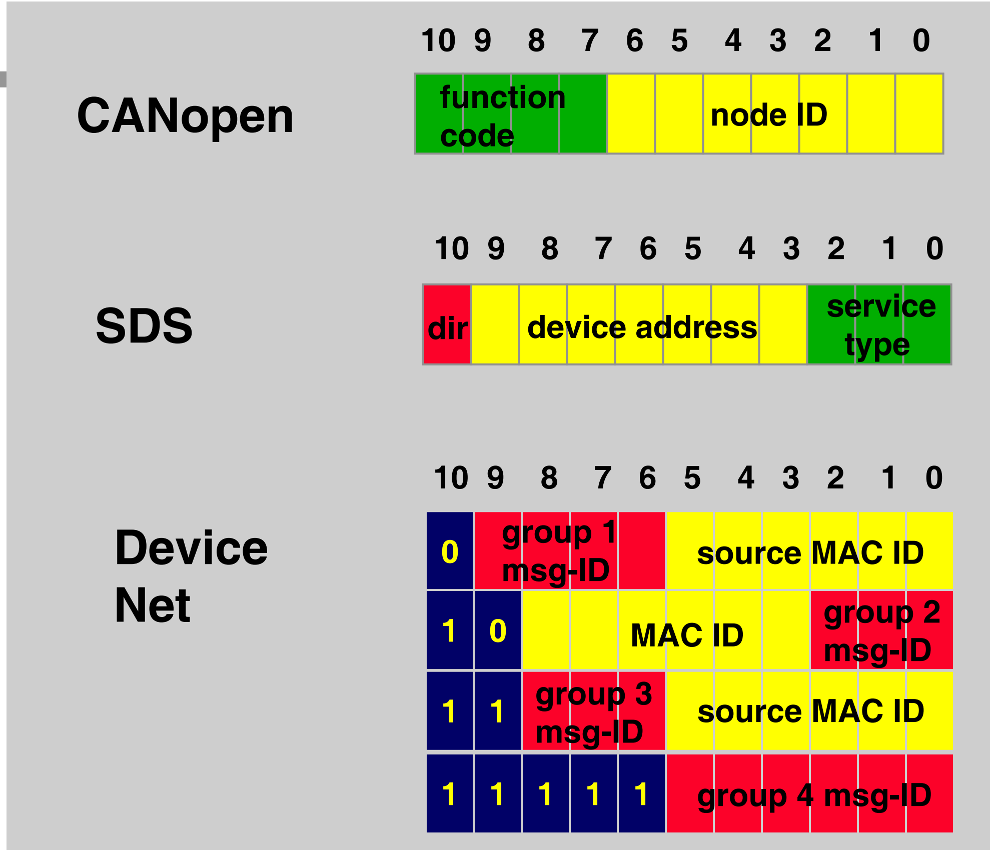
Network management issues

- node failure detection
- initialization control
- configuration control

Application Level Protocols

CANopen	CiA
SDS: Smart Device Systems	Honeywell
Device Net	Allen Bradley

CAN-ID Assignment



	#nodes	# ID:	# of free prio.:	prio. determined by:
CANopen	128	16/node	0	functions
SDS	128	16/node	0	direction/device
Device Net	64	32/node	32	message groups

Real-Time Support

Problem:

Priorities of messages are not orthogonal to issues of routing or service specification

Mechanism	CANopen	SDS	Device Net
restricted repetition rate	inhibit times	-	-
synch. by master	sync. Message	-	Master I/O Poll/Bit strobe
clock sync.protocol	high resolution	-	-
Bounds on service exec.		yes	

MAC-protocols