Real-Time Networks WorldFIP

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Outline

- WorldFIP history
- Architecture
- Physical layer
- Data link layer
  - Medium access control
  - Variable transfers
  - Message transfers
  - Consistency
- Temporal behavior
- Response time analysis

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History

- 1984: White paper
  - D. Galara, J.-P. Thomesse, “Groupe de réflexion FIP: proposition d'un système de transmission série multiplexée pour les échanges entre des capteurs, des actionneurs et des automates réflexes”, French Ministry of Industry, Paris, May 1984.
- 1989: French Standard (NF C46601-46607)
- 1996: European Standard (EN 50170)
- 2003: ISO/IEC standard (IEC 61158)

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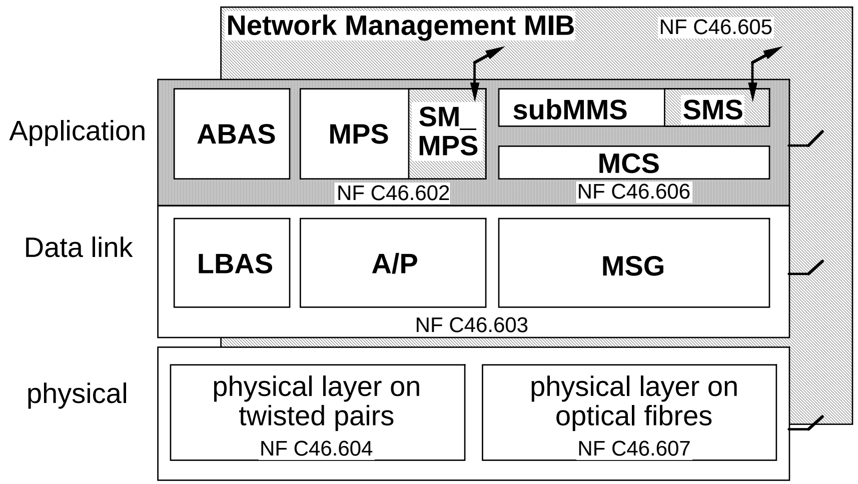
Architecture



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Basic Choices

- Real-time traffic consists of state information transferred in a cyclic or periodic manner but not event transmission
- All information is broadcast
- For real-time traffic,
  - only variables are identified (identifiers). Network nodes or application processes are not identified
  - the communication model is the Producer-Distributor-Consumer (PDC) Model where variable values transferred on the network are neither queued at production nor at reception
  - There is no retransmission and no acknowledge for real-time traffic
  - Consumers are responsible for checking transmission status and taking appropriate actions when problems arise

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Basic Choices (2)

- All variables transferred in real-time and their characteristics (period, relation with other transfers) are known in advance
- MAC handled by a unique active distributor. Backup allowed
- The response time is bounded between 10 and 70 bit times.
- Transfers are either periodic or sporadic.
  - The transfer period for the values corresponding to a variable may differ from the period associated to another variable. The only restriction is that periods should be integer multiples of a basic period.
- Mechanisms to indicate temporal validity as well as temporal and spatial consistency of variable values built in the protocol.
- The non real-time traffic handled using the conventional client-server model and the corresponding application is a subset of MMS (Manufacturing Message Specification).

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Physical layer

- twisted pairs (C46-604), optical fibers (C46-607)
- 3 speed classes
  - S1 (31.25 Kbits/s) / S2 (1 Mbits/s) / S3 (2.5 Mbits/s)
- Number of elements and range limited by
  - Propagation time Tp
    - normal case: Tp < 20 Tbit / extended: Tp < 40 Tbit
  - Losses and distortion on the cable
- 3 conformance classes
  - CH: high level class, allows long distance transmission at high data rates
  - CM: medium power class
  - CL: low power class for application with intrinsic safety requirements.
- recommended speeds
  - S1 or S2 for CL, S2 for CM, S2 or S3 for CH

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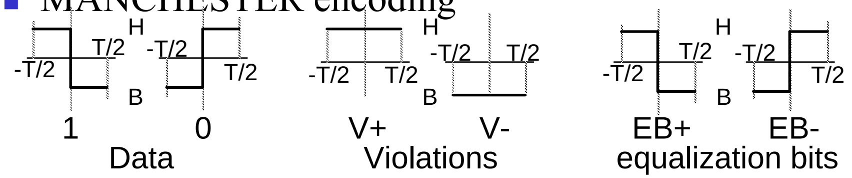
Coding

- balanced (bipolar) transmission
- MANCHESTER encoding



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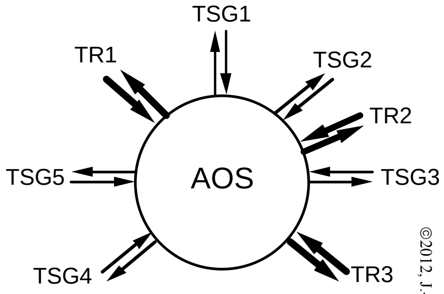
Optical physical layer

- identical to twisted pair one for:
  - Services, coding and transmission speeds
- restricted topology by exclusive use of active optical stars and point to point links
  - ⇒ special confirmation signal between 2 stars
- amplitude modulation of the optical signal (H symbol at higher level than B symbol)



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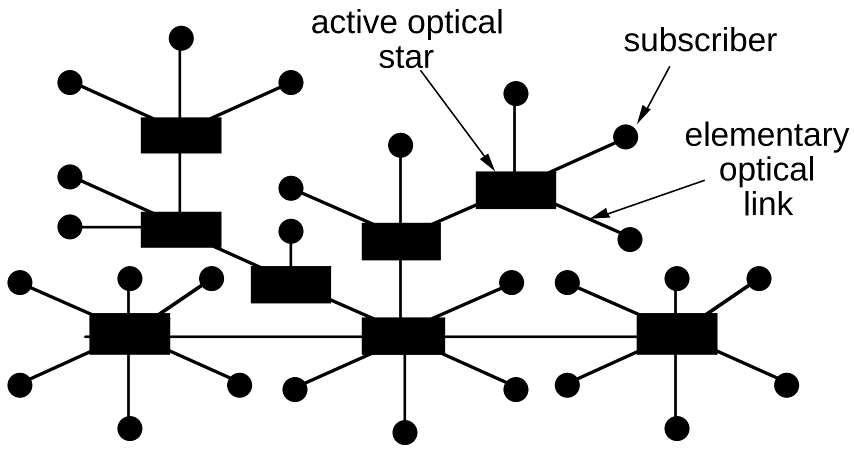
Topology using optical fibers



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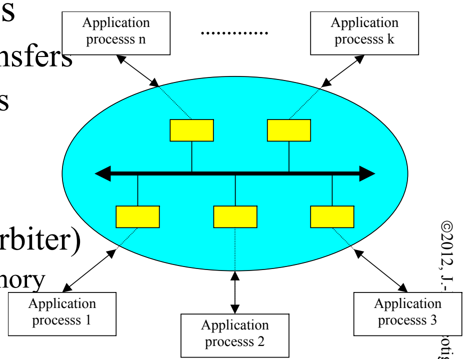
Data Link Layer

- makes use of cyclic nature of exchanges
  - nearly systematic use of broadcast
- centralized medium access control (bus arbiter)
- 2 types data transfer services
  - services used for variable transfers
  - services for message transfers
- 2 transfer types
  - on request
  - cyclic (triggered by the bus arbiter)
    - seems a distributed shared memory



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Addressing

- 2 different addressing spaces
  - For variables
    - identified by a unique identifier (16 bits) for each variable
    - address is not related to physical location
    - each variable producer and consumer(s) know the identifier of the variable
  - For messages
    - bear a source and a destination address (24 bits)
    - address is divided into a segment number (8 bits) and a LSAP (16 bits)

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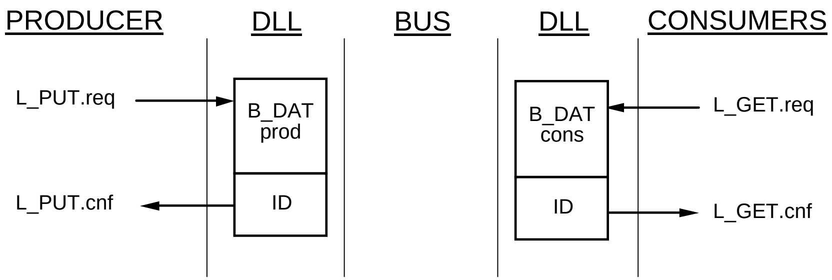
Variable transfers

- the DLL associates
  - a buffer (B_DATprod) to each identifier of produced variable
  - a buffer (B_DATcons) to each identifier of consumed variable



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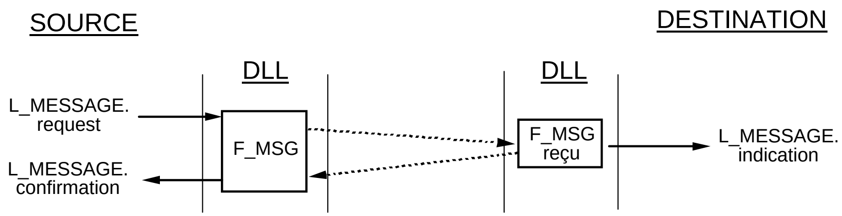
Message transfers

- the DLL associates
  - a queue (F_MSG) for the messages it needs to send
  - a queue (F_MSGreçu) for the messages that it receives



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Behavior

- variables
  - writing (reading) a variable does not trigger directly any traffic on the network
  - a new write operation overwrites the previous variable value
  - reception and emission of a value is signaled
    - → flow control possible (not necessary)
- messages
  - stored in a queue → no overwrite
  - transfer is signaled → flow control
  - duplications are avoided using alternating bit protocol

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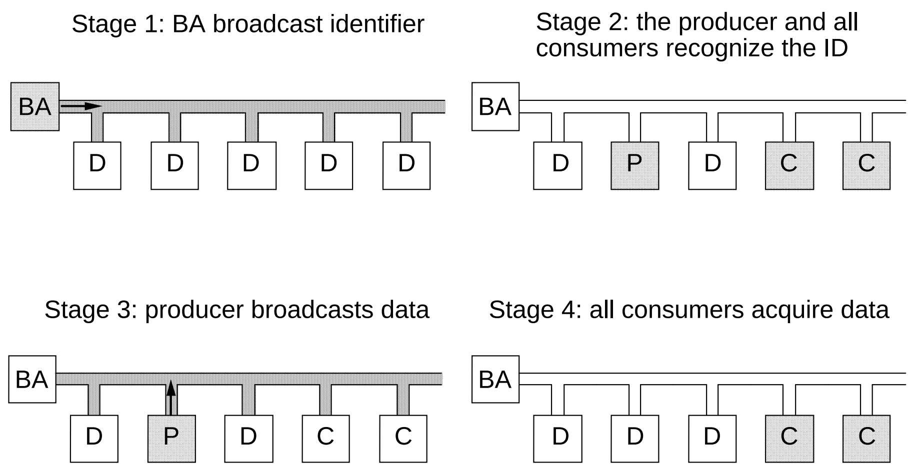
Medium access control



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Bus Arbiter (BA)

- control medium access
- a single one is active, however several may be in backup
- triggers all transactions
  - cyclic variable and message transfers
    - decided at configuration
    - configuration may be changed at run time
  - on-request variable and message transfers

As a station may not emit without being invited to, each station must possess a mean to inform the Bus Arbiter that it requests a transfer

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Signalling a request

- uses the periodic transfer of variables
- in its response to a periodic variable transfer invitation (from the Bus Arbiter), the producer DLL will indicate its request

a station that does not produce any periodic variable cannot explicitly require the transfer of a variable or a message

  - ⇒ message transfers are related to a variable identifier
- BA will later poll the requesting station to get the list of identifiers of the variables or messages for which a transfer is requested

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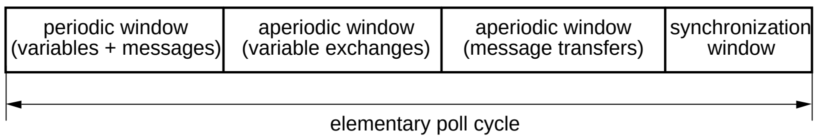
Operating principle

- according to configuration and explicit requests, the BA will establish a polling order



- the duration of the elementary polling cycle
  - is often constant (sampled data systems)
  - cannot exceed the duration of the smallest polling period requested by the users at configuration

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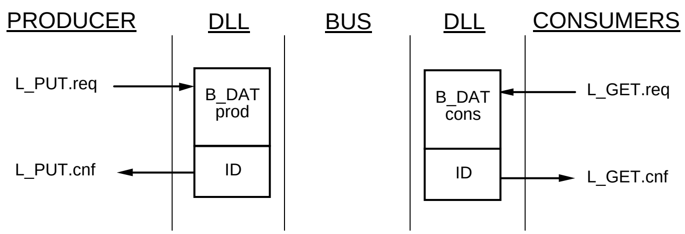
Read / write buffer services

- L_PUT/GET.request(identifier, value)
- L_PUT/GET.confirmation(identifier, status)
  - status gives the result:
    - result OK, unknown identifier, identifier invalidated by Network management, buffer access conflict, data length non compatible with buffer



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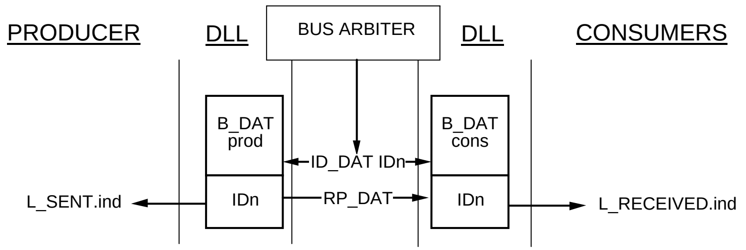
Buffer transfers

- 2 data units

ID_DAT	IDENTIFIER	FCS

RP_DAT	VARIABLE VALUE	FCS



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Explicit buffer transfer requests

- request signaled when responding to a periodic buffer transfer request (ID_DAT)
- 2 types
  - specified explicit request (identifier specified by DLL user)
  - free explicit request (identifier chosen by DLL)
- requester may be neither producer nor consumer of the variable
- the same identifier may not be used for both types of requests. It must be configured for a type of service

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Explicit buffer transfer requests (2)

- BA later polls the requesting node for the list of identifiers of variables and messages for which a transfer is requested
- BA establishes a list of pollings (ID_MSG or ID_DAT) to fulfill the requests
  - If the same ID is requested while already requested, only one request is assumed

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Explicit transfer requests

- specified explicit request
  - requests are not queued inside DLL (buffer B_REQ)
  - and are served either
    - immediately in the periodic window (RQ_INHIBE true)
    - or in an aperiodic window (RQ_INHIBE false) with urgent priority
- free explicit request
  - requests are queued (file F_REQi) according to priority (i=1 or 2)
  - are served according to the priority (1: urgent or 2: normal) in an aperiodic window

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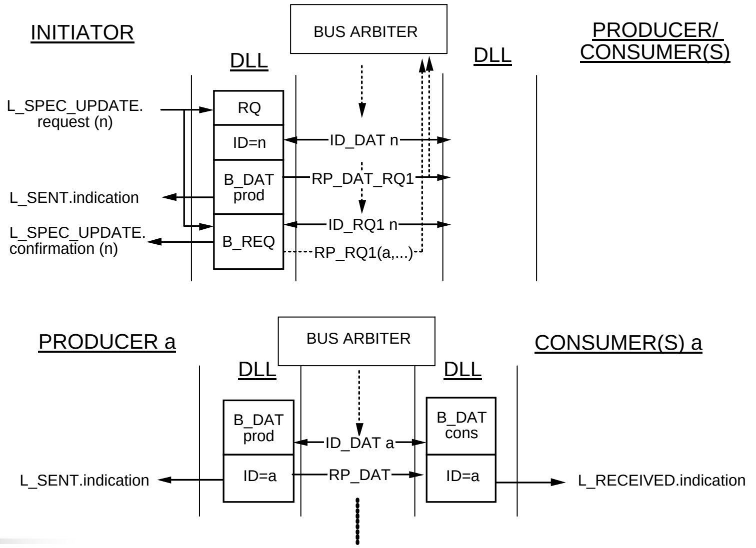
Specified explicit request (RQ_Inhibe false)



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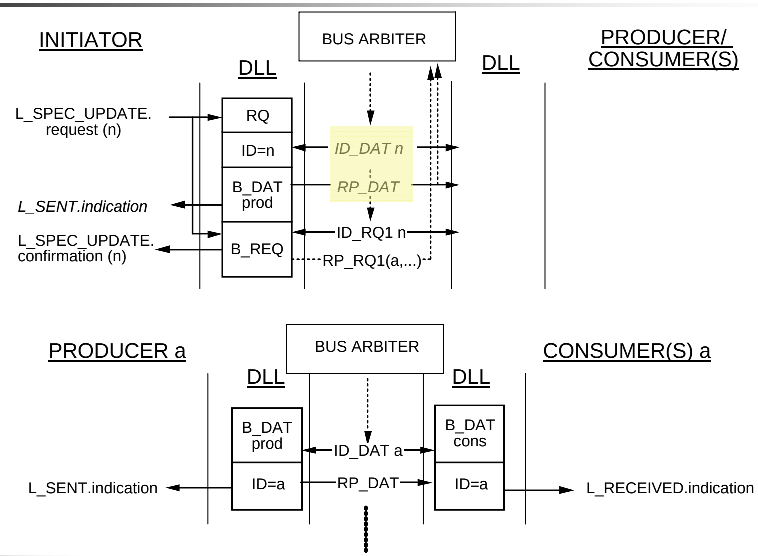
Specified explicit request (RQ_Inhibe true)



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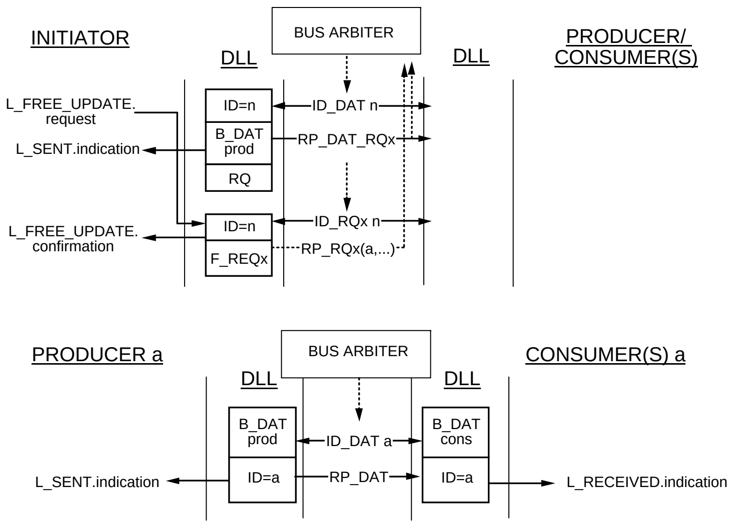
Free explicit requests



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Message transfer services

- with (point to point only) or without acknowledge (protection against loss and duplication by alternating bit)
- requests are served in
  - the periodic window (cyclic msg transfers)
    - → resources allocated at configuration
  - the aperiodic window (aperiodic message transfers)
    - → requests queued in file F_MSGaper
- multisegment transfers
  - only point to point
  - go through a bridge (ack sent by bridge)

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Cyclic message transfers

- use one or more variable identifiers configured for this type of transfer. The same Ids may be used for buffer transfer.
- a file (queue F_MSGcyc) is associated to each identifier
- messages stored in the F_MSGcyc queue associated to the identifier indicated in the request
- request served in the periodic window (even if no msg pending)
- transfer is performed with or without ack

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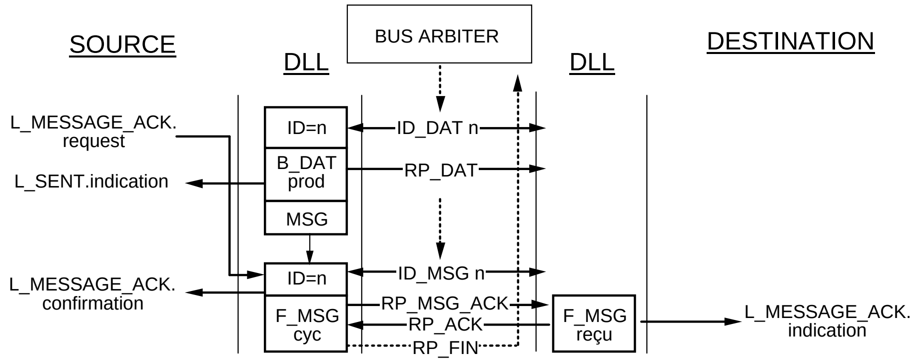
Cyclic message transfers (2)



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Aperiodic message transfers

- no identifier is indicated in the request
- identifier is chosen by the DLL
  - it must be configured for this type of service
  - it must correspond to a variable produced by the given station(source of message)
  - it must be already associated to a message in the queue
- the request is signaled to the bus arbiter in the response to an ID_DAT frame with the selected identifier
- association with the identifier is cut when the message has been transferred. The ID may then be used for another message in the queue

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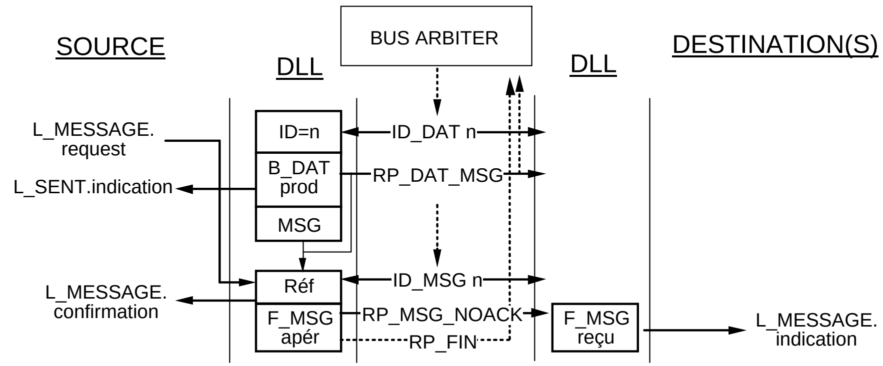
Aperiodic message transfer



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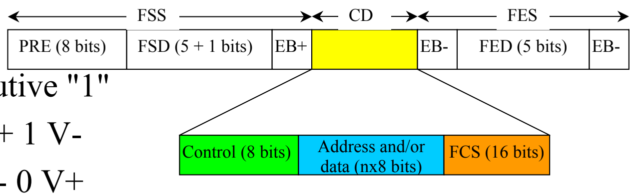
Frame Format



- PRE = 8 consecutive "1"
- FSD = V+ V- V+ 1 V-
- FED = V- V+ V- 0 V+
- FCS= CRC 16 (CCITT V41) on CD field

Frame Type	Data / address field (CD field)
identifier (ID_xyz)	Identifier (2 bytes)
Response request (RP_RQx)	List of identifier of requested var. transfers (≤ 64 ids)
Response message (RP_MSG)	Source + destin. Addr. (2x24 bits) + message (≤256B)
Response data (RP_DAT_z)	Data (up to 128 bytes)
Other frames	empty

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Timers

Name	Localization	Function	Value
T0		Return time	
T1	Active BA	Absence of RPxx after IDxx	T0
T2	Active BA	Filling synchronization window	EC time
T3	Potential BAs	Absence of IDxx after RPxx	K*N*T0
T4	Consumer	no RP_DAT_xx after ID_DAT	T0
T5	Active BA	no RP_FIN after ID_MSG	2*T0
T6	Source of msg	no RP_ACK after RP_MSG_ACK	T0

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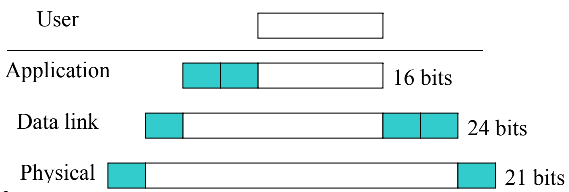
Importance of timer T0

- T0 = TR Tmac with $10 \leq TR \leq 70$
- number of bits in a frame = 61 bits + 8 n



- transaction duration = 61 Tmac + (61+8n) Tmac + 2 T0

T0	n	Efficiency	Thoughput (@1Mbit/s)	Duration [µs]
10	2	10.1 %	101.3 Kbit/s	158
70	2	5.8%	57.6 Kbit/s	278
10	10	36%	360 Kbit/s	222
70	10	23%	234 Kbit/s	342

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Spatio-temporal aspects

- for periodicity
  - centralized medium access control
  - mandatory maximum return time
- for validity duration
  - refreshment status
  - promptness status
- for temporal consistency
  - based upon refreshment and promptness statuses
- for spatial consistency
  - broadcast of consistency variable

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List concept

- ordered collection of consumed variables
- lists should not intersect in the system
- variables may be periodic or not
- periods may be different
- temporal consistency may be defined on a list

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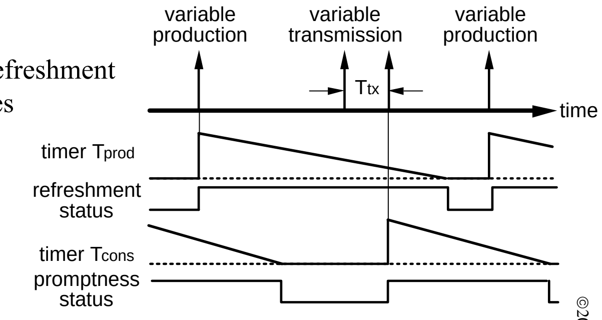
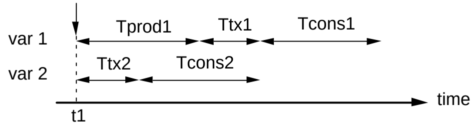
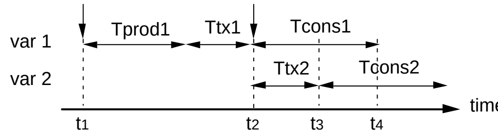
Temporal consistency

- asynchronous status
  - Ttx + Tcons ≤ Tvalidity ≤ Ttx + Tprod + Tcons
- temporal consistency
  - = logical AND of all refreshment and promptness statuses
    ⇒ problems







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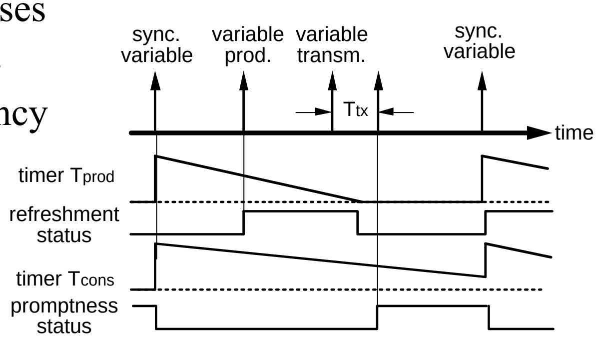
Temporal consistency (2)

- synchronous statuses
  - Tvalidity = Tcons
- temporal consistency
  - = logical AND of all refreshment and promptness statuses



⇒ OK as long as the same sync. variable is used for all

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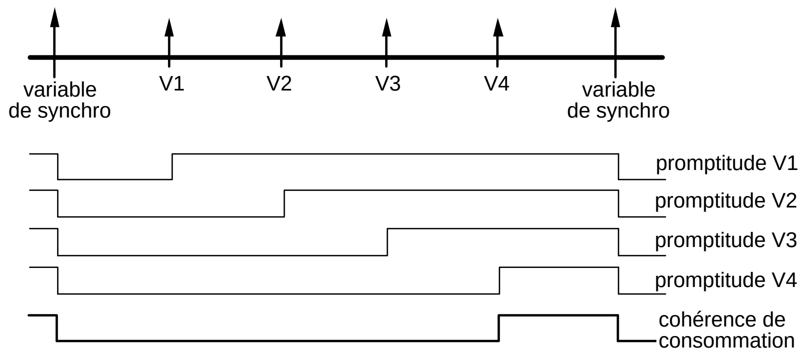
Temporal consistency (3)



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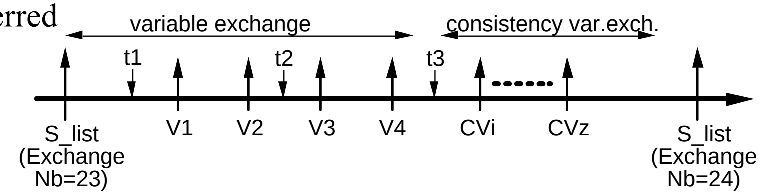
Spatial consistency

- may only be elaborated on lists
- based upon two types of variables
  - a synchronization variable
    - its value corresponds to the exchange Nb
  - a consistency variable for each consumer
    - bears the exchange Number / indicates for each variable in the list
  - either the exchange number of the available variable value (maintained detection) or the indication of reception in the current exchange cycle (instantaneous detection)
- at the end of variable transfers, the consistency variables are transferred



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Temporal behaviour

- Central polling
  - Guaranteed transaction time (ID_xxx + RP_yyy) provided each transactions is bounded
    - Timer T0
  - Scheduling algorithm is not specified
- Periodic operations possible
  - Also with multiple periods
- No retransmission in case of errors
  - Except for messages with ack
  - Oversampling may be necessary to tolerate absence of a value in case of error (vacant sampling)

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Temporal behaviour (2)

- Sporadic traffic
  - Best effort (except for specified explicit requests handled in periodic window)
  - Handling order not specified (may be FIFO)
  - 2 priorities
  - No admission control

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Schedulability analysis

- Periodic traffic
  - Assumed to be guaranteed so worst case is to be considered
    - Variable transfers + non acknowledged messages
    - Acknowledged messages
- Aperiodic (sporadic) traffic
  - May be analysed in worst case or statistically
    - Statistics are interesting to take errors (retries) into account

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Periodic traffic

- $P_i=\{C_p, D_i, T_i\}$; length, deadline, period
- Elementary cycle (EC): duration T_{mc}
  - GCD(T_i) or using the cyclic executive principle [Bak89]
- Macrocyle = LCM (T_i)
- May be scheduled off line or on line
  - Enough time should be left to accomodate a single aperiodic transfer of the longuest duration T_{data}^{max}
  - Number of transfers that can be scheduled in an EC

$$N_p = \left\lfloor \frac{T_{mc} - T_{data}^{max}}{C_p} \right\rfloor$$

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Transaction duration (@ 1 Mbit/s)

- Message with acknowledgement (K-1 retries)
  - Max length (254 byte message)

$$\begin{aligned} T_{data}^{max} &= \{ID\_MSG + RP\_FIN\}T_{mac} + (2K+2)T_0 \\ &+ K(RP\_MSG\_ACK + RP\_ACK)T_{mac} \\ &= \{61+45\} + 8 \bullet 70 + 3(2141+45) = 7224\mu s \end{aligned}$$

  - Max length (8 byte message, 2 retries) = 1320µs
- Variable
  - Max. length (8 byte payload) = 61+125+2*70=326 µs

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Schedulability of periodic traffic

- Assume N_p transactions per EC
- Priorities according to RM or DM
- If there are no gaps, the m-th transaction will be handled at: $t = \left\lfloor \frac{m-1}{N_p} \right\rfloor T_{mc} + \{(m \; MOD \; N_p) + 1\} C_p T_{mac}$
- The first transaction of the i-th periodic flow will be the m-th transaction where m is given by

$$m = 1 + \sum_{j \in hp(i)} \left\lceil \frac{t}{T_j} \right\rceil$$

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Example [Tov99a]

- Example used for Profibus
- Assume high priority is made of synchronous messages
  - Period is equal to deadline

	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6
$Dh_1(m)$	50 ms	90 ms	120 ms	60 ms	60 ms	80 ms
$Dh_2(m)$	100 ms	80 ms	130 ms	200 ms	100 ms	80 ms
$Dh_3(m)$		140 ms	110 ms	140 ms	100 ms	100 ms
C	1.32	1.32	1.32	1.32	1.32	1.32
nlp	3	3	3	3	3	3

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Example (2)

- HCF= 10 ms
- LCM = 3603.600s
- Implementation using FIP messages (max. 2 retries)
  - Synchronous window= 4 ms (3 periodic messages per EC)
    - 1’081’080 messages in LCM (need is 1’007’279)
  - Deadlines (priorities according to DM)

	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6
Dh_1(m)	50 /1.32	90 / 21.32	120 / 41.32	60 / 2.64	60 / 3.96	80 / 11.32
Dh_2(m)	100 / 22.64	80 / 12.64	130 / 42.64	200 / 53.96	100 / 23.96	80 / 13.96
Dh_3(m)		140 / 43.96	110 / 33.96	140 / 52.64	100 / 31.32	100/ 32.64
C	1.32	1.32	1.32	1.32	1.32	1.32

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Response time analysis

- Asumptions [Ped97]
  - Periodic variables (no message)
  - Aperiodic (sporadic traffic) variables (no message)
    - Deadline ≤ period (no more than
  - Free explicit requests (2 priorities)
  - Requests are queued in FIFO order at BA
  - All periodic traffic has the same length C_p

$$C_p = (len(ID\_DAT) + len(RP\_DAT))T_{mac} + 2T_0$$

  - All aperiodic traffic has the same length C_a
  - Duration of periodic window is fixed T_s^{max}

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Worst case

- Queueing time
  - When a variable (message) transfer request is queued in BA after all other variables and messages
- Dead interval (maximum interval between 2 pollings of a node) σ_k
  - When a request arrives at a node just after the periodic variable transfer took place

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Temporal analysis

- Request at time t
- Will be signalled to BA at time t+σ_k at latest
- Identifier will be known to BA after the list will have been transferred
  - δ_{pa}(k) is the time to collect the list of identifiers for that station
- Pending aperiodic traffic must be transferred
- Periodic traffic is transferred in between

$$R_n = \sigma_k + \delta_{pa} + T_s^{max}\left\lceil \frac{R_n - \sigma_k}{T_{mc}} \right\rceil + \sum_{\forall j \in S_x} C_a$$

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Response time parameters

$$R_n = \sigma_k + \delta_{pa} + T_s^{\max}\left\lceil \frac{R_n - \sigma_k}{T_{mc}} \right\rceil + \sum_{\forall j \in S_x} C_a$$

- δ_{pa}

$$\delta_{pa} = n_s(ID\_RQ + RP\_RQ)T_{mac} + 2n_sT_0$$

  - n_s number of stations that generate sporadic traffic
- S_x is the set of generated sporadic traffic between t and t+Rn
  - All urgent sporadic variables if we evaluate Rn for an urgent stream
  - All sporadic variables otherwise

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Example 2

- 6 nodes, 3 streams each, 50 ms worst case interrival time (is also deadline)
- High priority traffic implemented as variable transfers with oversampling 3 times (all periods divided by 3)
- Buffer transfer (variable) time = 326 µs (appx 1/3 ms)
- EC duration T_{mc}= 10/ 3 ms; hyperperiod = 1201.2 s

	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6
$Dh_1(m)$	16.67 /0.33	30 / 7	40 / 13.67	20 / 0.67	20 / 1	26.67 / 3.67
$Dh_2(m)$	33.3 / 7.33	26.67 / 4	43.3 / 14	66.7 / 17.67	33.3 / 7.67	26.67 / 4.33
$Dh_3(m)$		46.67 / 14.3	36.67 / 11	46.67 / 17.3	33.3 / 10.33	33.3/ 10.67
C	0.33	0.33	0.33	0.33	0.33	0.33

- Synchronous window: $T_s^{\max}$ = 1ms

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Example 2 (2)

$$R_n = \sigma_k + \delta_{pa} + T_s^{\max}\left\lceil \frac{R_n - \sigma_k}{T_{mc}} \right\rceil + \sum_{\forall j \in S_x} C_a$$

- δ_{pa} : 6 nodes, 1 Mbit/s, ID_RQ length= 61 bits
  - RP_RQ length = 61 + 16 * Nb_Identifiers = 109 bits
  - (61+109+2*70)*6=1860

	Prod 1	Prod 2	Prod 3	Prod 4	Prod 5	Prod 6
σ_k	16.67	26.67	36.67	20	20	26.67
δ_{pa}	1.86	1.86	1.86	1.86	1.86	1.86
R_n	53.3	63.3	73.3	56.5	56.6	63.3
C	1.32	1.32	1.32	1.32	1.32	1.32

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Analysis

- Compared to Profibus
  - FIP suffers from the dead time for sporadic traffic response deadline
    - This is true only for traffic coming from a master station
  - Provided the token rotation time is set adequately, performances are comparable if we allow retries
  - FIP can provide periodicity and multiple periods

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Summary

- FIP is interesting to handle periodic traffic
- Bounds can be derived for sporadic traffic
  - But are directly linked to polling periods
- FIP has mechanisms to indicate temporal validity and consistency
  - Validity may not be needed in the case of other solutions
- Thanks to broadcast source addressing, multicast is easily implemented
- Timer T0 proves to be critical in the performances

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