Engineering Hybrid Wired/Wireless Fieldbus Networks - a case study

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Abstract

Advances in networking and information technologies are transforming factory-floor communication systems into a mainstream activity within industrial automation. It is now recognized that future industrial computer systems will be intimately tied to real-time computing and to communication technologies. For this vision to succeed, complex heterogeneous factory-floor communication networks (including mobile/wireless components) need to function in a predictable, flawless, efficient and interoperable way. In this paper we re-visit the issue of supporting real-time communications in hybrid wired/wireless fieldbus-based networks, bringing into it some experimental results obtained in the framework of the RFieldbus ISEP pilot [5].

1. A hybrid wired/wireless fieldbus

1.1 Basics on a hybrid wired/wireless architecture

A traditional fieldbus network consists of several nodes physically connected through a wired bus. Therefore, and due to market penetration, thinking about wireless means considering hybrid wired/wireless solutions able to inter-operate with legacy (wired) systems. We assume hybrid wired/wireless network topologies such as the one depicted in Figure 1, where PROFIBUS is considered as the federating system [1].

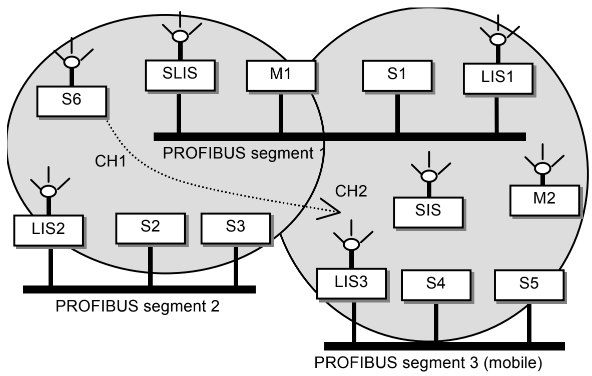

Figure 1: Hybrid wired/wireless network

Wired network master (M) and slave (S) nodes communicate with wireless/mobile nodes through Intermediate Systems (ISs), which can be of three types: Linking ISs (LISs); Structuring ISs (SISs); and Structuring and Linking ISs (SLISs). The latter merge the functionality of LISs and SISs. Additionally, mobility of wired PROFIBUS segments (and associated stations) is also considered (segment 3). For the example scenario, the SLIS and the SIS structure the wireless part of the network in two different radio cells, operating in different radio channels (CH1 and CH2, respectively), in order to support inter-cell mobility [2].

ISs operate at the Physical Layer level, leading to a broadcast network (stations receive every transmitted frame), with a unique MAC address space and a unique logical ring. PROFIBUS v1 (RS-485, asynchronous) is considered as the wired physical medium and the wireless physical medium is based on IEEE 802.11b [2].

A mechanism for supporting inter-cell mobility for all types of mobile stations is described in [1]. Due to the broadcast nature of the network, the use of explicit registration mechanisms could be avoided (the mobility management mechanism was almost reduced to a procedure for radio channel assessment and switching).

The *mobility master (*MobM*)* triggers the procedure by broadcasting a *Beacon Trigger* (BT) frame (Figure 2). SISs/SLISs start transmitting beacons in their own radio channel (CH1, CH2) and every wireless/mobile station (e.g. S6) is expected to assess the quality of the different radio channels, switching to the best quality one (CH2, assuming that S6 is moving to that radio cell).

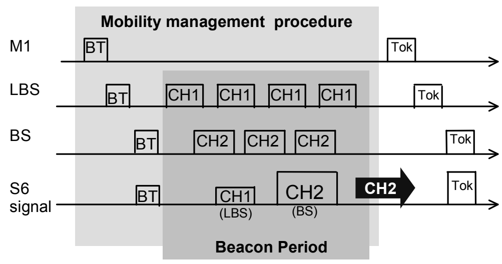

Figure 2: Mobility management timing diagram

Importantly, this mechanism guarantees no loss of data and permits to fulfil stringent real-time requirements. In fact, mobility management is restricted to a reduced and bounded period of time (typically below 4 ms overhead per second) [1].

1.2 Analytical models for the network

In order to analyse and guarantee the real-time behaviour of such a network, there was the need to define the characteristics of all network components, namely the ones that most affect the timing behaviour of the network. A complete analytical model for the addressed hybrid network was proposed in [3], covering the definition of attributes and timing behaviour for network components such as (wired and wireless) domains, end-systems, intermediate systems and physical media. In this paper, we will only briefly outline the models of the intermediate systems and of the physical media.

Defining a model for the Physical Media (e.g. bit rate and PhL frame format) is mandatory to compute the duration of a PhL frame and characterising the relaying behaviour of an IS. A physical medium (*M*) is defined by the following parameters: r - bit rate; l_H - overhead of the head per PhL frame; l_T - overhead of the tail per PhL frame; k - overhead per char for the PhL protocol; o - offset defining the total number of bits until knowing the length of the data field (Figure 3).

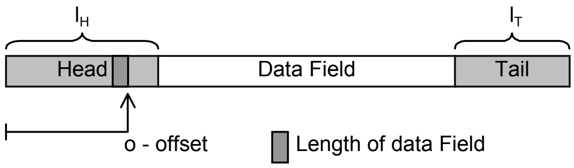

Figure 3: Generic format of a PhL frame

The offset o is relevant for the definition of the relaying behaviour of the ISs, as briefly described next.

The model for the intermediate systems proposed in [3] enables the definition of a minimised latency repeater (cut-through behaviour); that is, it permits to define a profile for a repeater that starts relaying PhL frames as early as possible. An Intermediate System is defined by several parameters, such as its type (SIS, LIS, SLIS) and the type of physical media it interconnects. Additionally, a start-relaying instant function – $t^{i\to j}_{sr}$ – determines the earliest time instant for start relaying a specific PhL frame from a communication domain D^i to a communication domain D^j, counted since the beginning of the PhL frame in domain D^i. It is assumed that relaying cannot start: while the first char of DLL data is not available (data ready - t_{dr}); while the length of the DLL frame is not known (length known - t_{lk}); the transmission of a PhL frame in D_j must be continuous, without time gaps (no gaps - t_{ng}). The start-relaying instant for a cut-through IS is defined as (Figure 4):

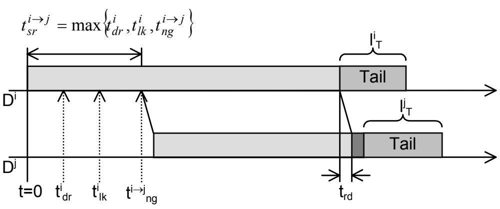

Figure 4: Relaying behaviour of a cut-through IS

2. Guaranteeing real-time communications

Several methodologies were proposed in [3] to guarantee the real-time behaviour of the hybrid network. This involves computing and setting several parameters: the Idle Times that must be inserted (by every master) in order to adapt different PhLs, the Slot Time and worst-case duration of message transactions, and the parameters for the mobility management mechanism.

2.1 Adapting heterogeneous physical media

In PROFIBUS, a response to a request has to be received within the Slot Time (T_{SL}), otherwise the master retries the request (token) or aborts the transmission. In a hybrid broadcast network such as the one considered, message turnaround times increase due to the relaying latencies in the ISs (Figure 5):

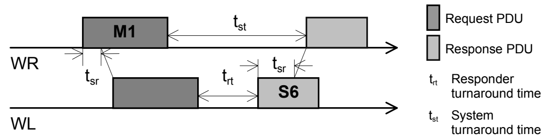

Figure 5: Responder and system turnaround times

Additionally, frames may be affected by unbounded queuing delays in the ISs, due to the interconnection of different physical media (bit rates and frame formats). Therefore, an upper limit for the system turnaround time of a message transaction could not be computed if an appropriate adaptation mechanism was not provided. A solution is to delay request frames through the insertion of additional idle time, in master stations [3,4] (Figure 6).

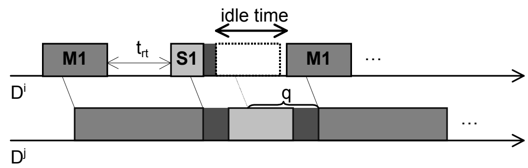

Figure 6: Inserting idle time to adapt different media

Importantly, this mechanism relies of standard features of the PROFIBUS protocol – the Idle Time parameters.

2.2 Computing T_{SL} and C_{ack}

In order to set an appropriate value for the Slot Time (T_{SL}) parameter, it is necessary to compute t_{st} (worst-case system turnaround time) for every possible message transaction in the network. The work described in [3] proposes methodologies in order to compute the Slot Time parameter – T_{SL}, and also the worst-case duration of every message transaction (C_{ack}):

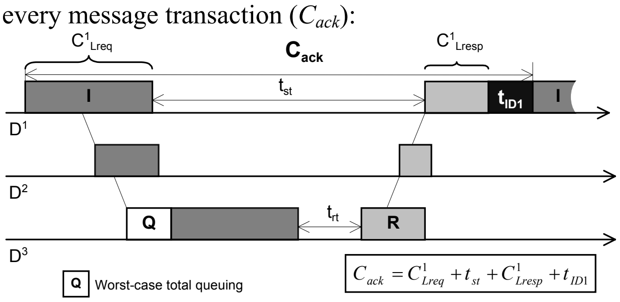

Figure 7: Duration of a transaction (C_{ack})

2.3 Computing the mobility management parameters

In [3] the evaluation of the proper value to set T_{ID2} in the mobility master, which is related to the worst-case duration of the mobility management procedure, is also detailed. This worst-case duration depends on the number of beacons that each SIS/SLIS must transmit, after having received (and relayed) the BT frame (can be different for every SIS/SLIS). Therefore, it is mandatory to compute the optimal (minimum) number of beacons (n_b) to be transmitted by each SIS/SLIS.

3. System planning application

The computation of all parameters is quite complex, time-consuming and error-prone (e.g. calculation errors or missing of alternative paths due to mobility). These issues triggered the need to develop of a System Planning Application (SPA) to reduce the complexity and the time spent in system design and to minimize the probability of errors. This tool was successfully used to engineer the RFieldbus system described in [5].

The SPA user creates a virtual image of the network topology by dragging items from a toolbox (Figure 8, left) into the drawing area (Figure 8, right).

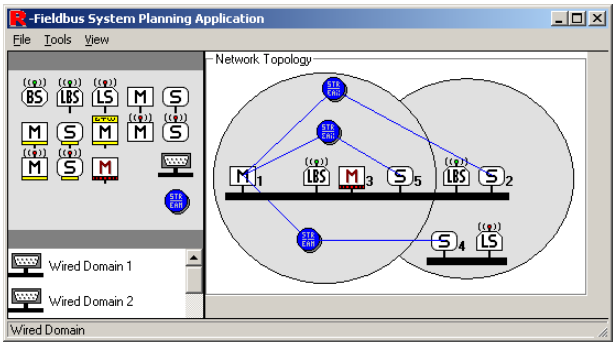

Figure 8. System Planning Application

When adding a new station, it will be automatically assigned an unused address. To add one wireless domain (represented by an oval gray area), we have to add one structuring intermediate system (Base Station – BS, or Link Base Station - LBS). To add a message stream, the user selects the Message Stream tool and then clicks in the Initiator and Responder (e.g. M1 and S2). Multiple message streams between two stations are grouped into the same connector. The physical media must be defined by setting the appropriate parameters (Figure 9).

After having configured all input parameters, the application computes the parameters for setting up the network. First, the network topology is verified to avoid closed-loops. Then, all alternative paths (due to mobility) are determined, for every message stream. Finally, all the parameters are computed and the main results window is presented (e.g. Figure 10), as briefly outlined next.

For the example scenario shown in Figure 8, two types of physical media are configured as shown in Figure 9, corresponding to the ones defined in the RFieldbus framework (1 – wired (PROFIBUS v1), 2 - Wireless).

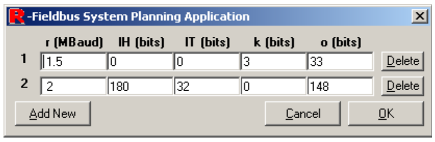

Figure 9. Physical media parameters

The first wired segment (topmost in Figure 8) includes four stations: M1 – Master, M3 – Mobility Master, S2 and S5 - Slaves, and two structuring intermediate systems (two Link Base Stations). The second segment holds a single station: S4 – Slave, and one intermediate system (a Link Station). The results are shown in Figure 10.

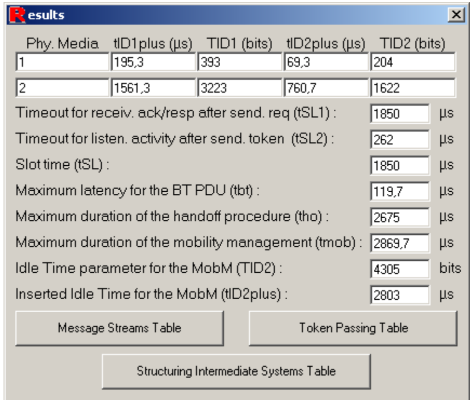

Figure 10. The main results window

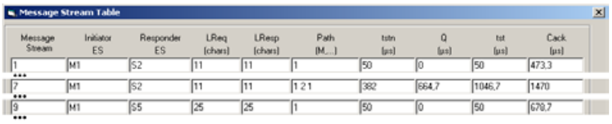

Figure 11. The results window for message streams

Each LBS must transmit 22 beacons, as detailed in the "Structuring Intermediate Systems Table" (not shown here).

4. Theoretical vs. experimental results

In this section, the worst-case results output by the System Planning Application (SPA) are compared against measurements carried out using a network analyser, in order to analyse their validity and degree of pessimism. When matching theoretical with experimental results, for the case study described in the previous section, an unexpected timing behaviour was noticed. A closer study led to the conclusion that the RFieldbus boards [6] introduce additional delays, both when acting as responder and as initiator. As a responder, this delay has a considerable influence on the turnaround times (t_{rt}, t_{st}) of every message stream. As an initiator, this impacts T_{ID1} and C_{ack}. Therefore these delays must be considered in the theoretical computation, as follows.

For the responder, $T_{rt\_min} = 15$ and $T_{rt\_max} = 75$ bit times were originally assumed as realistic values, because native PROFIBUS slave boards (e.g. PLC) usually have a short T_{rt}. After several measurements, it was concluded that the RFieldbus boards may have turnaround times of almost 400 bit times. For instance, this was noticed for the message transaction between two PC's in the same domain (Figure 12). The T_{st} of 270 bit times is much higher than the worst-case value of 75 bit times initially assumed as input to the SPA. These additional delays must be taken into account, by changing the T_{rt_min} and the T_{rt_max} parameters in the SPA, according to the real $T_{rt\ min}$ = 12 bit times and T_{rt_max} = 370 bit times that were measured.

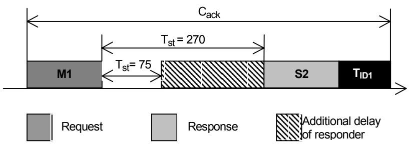

Figure 12. Transaction for message stream 1

Let's now address the case where the RFieldbus board is used as initiator. The value of 393 bit times for T_{ID1}, calculated by the SPA Figure 10, is indirectly set in the configuration file of the master by manipulating the min T_{SDR} parameter. Figure 13 depicts a message transaction between the master and the PLC. The inactivity time measured between receiving the response and transmitting a request is 562 bit times. Therefore, we conclude that the RFieldbus board in the master (initiator) inserts an additional inactivity time of around 250 (=562-393) bit times, which happens for every message transaction. This problem can be solved by setting T_{ID1}=143 (=393–250) bit times, in the master.

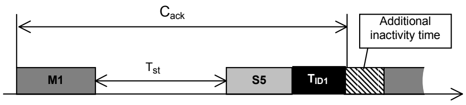

Figure 13. Transaction for message stream 9

The same conclusions could be drawn for a stream between two PC's in different domains (Stream 7, Figure 14). The only difference is that in most cases it is not possible to notice the delay inserted by the slave RFieldbus board, because the SPA takes the Q into account for the computation of both T_{st} and C_{ack}.

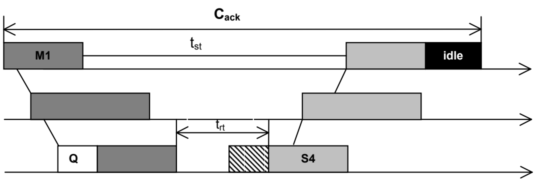

Figure 14. Transaction for message stream 7

Table 1 depicts the (re)-computed worst-case and the measured durations for the three streams.

Message Stream	C^{WC}_{ack} *(bit times)*	C^{M}_{ack} *(bit times)*	*Pessimism (%)*
1	1008	916	10
9	1317	966	36
7	2504	1400	79

Table 1. Worst-case vs. measured C_{ack} (C^{WC}_{ack}, C^{M}_{ack})

The table also provides a column with the pessimism introduced by the SPA, which is calculated as $[(C^{WC}_{ack}/C^{M}_{ack})-1]\times100\%$.

For stream 1, where the initiator and responder are in the same domain, T_{st}=T_{rt_max}=370 bit times. Since the actual T_{st}=270 bit times, there is a pessimism of 10% ($C^{WC}_{ack} \approx C^{M}_{ack}+T_{rt\_max}-T_{st} \approx$ 916+370-270≈1008 bit times). For stream 9, the fact that the actual T_{st} for the PLC is equal to $T_{rt\ min}$=12 bit times, it results in a pessimism of 36% (C^{WC}_{ack}≈966+370-12≈1317 bit times). Message streams with initiator and responder situated in different domains often have more pessimistic results. This is because Q is taken into account in the worst-case analysis and real queuing delay in the case study depends on the amount of traffic in the network. Therefore, the pessimism for stream 7 is 79%.

5. Conclusions

This paper started by summarizing the most important architectural issues for a hybrid wired/wireless fieldbus network based on the PROFIBUS protocol. Then, it outlined several aspects of paramount importance for guaranteeing real-time communications in such a network. The basics of a System Planning Application (SPA) were also presented. This tool turned out to be very important to compute all relevant parameters for putting the hybrid network into operation. Obviously, its advantages increase as networks get more complex, since manual computation would be very time consuming, complex and, most probably, involving errors. Finally, theoretical worst-case results were compared against experimental results, for a scenario within the context of the manufacturing automation field trial of the RFieldbus project. The use of both the SPA and a network analyzer permitted to analyse the validity and degree of pessimism of the theoretical results and also to detect some unexpected delays in the RFieldbus boards.

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