Formal specification of the FlexRay protocol using Focus\textsuperscript{ST}

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Abstract:
FlexRay is a communication protocol developed by the FlexRay Consortium. The core members of the Consortium are Freescale Semiconductor, Robert Bosch GmbH, NXP Semiconductors, BMW, Volkswagen, Daimler, and General Motors, and the protocol was respectively oriented towards embedded systems in the automotive domain. This paper presents a formal specification of the FlexRay protocol using the FocusST framework. This work extends our previous research of formal specifications of this protocol using Focus formal language.

1 INTRODUCTION

The FlexRay Consortium developed approx. 20 years ago a time-triggered protocol for embedded systems in vehicles, cf. [22]. The core advantages of this protocol, in comparison for event-driven protocols, are deterministic real-time message transmission, fault tolerance, integrated functionality for clock synchronisation, and higher bandwidth. FlexRay static cyclic communication schedules and system-wide synchronous clocks allow to apply distributed control algorithms used in drive-by-wire applications.

In our previous work [31, 18, 19, 20], we introduced the FlexRay specification using the Focus specification language [6] and the corresponding verification using the Isabelle/HOL theorem prover [23], cf. also [31, 32, 37]. That formalization was based on the “Protocol Specification 2.0”[12].

In this paper we present an extended version of this specification: we apply the Focus\textsuperscript{ST} framework to allow for a better readability as well as highlighting the timing aspects of the specification.

Outline: Section 2 introduces the basic principles of the Focus\textsuperscript{ST} framework. Section 3 presents the core features of the FlexRay protocol along with their formal specifications in Focus\textsuperscript{ST}. Section 4 discusses the related work. Finally, Section 5 summarises the paper.

2 FOCUS\textsuperscript{ST}

Focus\textsuperscript{ST}[39, 41] is an extension of the Focus framework to increase the readability and understandability of the formal specification. The Focus\textsuperscript{ST} specification layout is similar to Focus, but it has a number of new features based on human factor analysis within formal methods, cf. [46, 34, 36].

The first step towards elaboration the Focus\textsuperscript{ST} framework was the optimisation of the Focus specification layout were discussed in [35]. In both frameworks, specifications are based on the notion of streams, but the formalisation of this concept is done in different ways: The input and output streams of a Focus component are mappings of natural numbers N to single messages and, in the case of timed streams, \sqrt{presenting the clock ticks. The Focus\textsuperscript{ST} input and output streams of a component are always timed. They are formalised as a mapping from N to lists of messages that are transmitted within the corresponding time intervals. Thus, Focus\textsuperscript{ST} has streams of two kinds (T\ast denotes a list of elements of type T):

- Infinite timed streams M\infty to specify the input and the output streams are formalised by \(N \rightarrow T\ast\);
- Finite timed streams M\infty to specify timed streams truncated at some point of time are formalised by \((T\ast)\ast\).
3 FLEXRAY PROTOCOL

A FlexRay-based system is built from a number of nodes, connected via a network cable. The nodes might have different configurations. On each node

- a FlexRay Controller is running (a network cable connects the FlexRay controllers of all nodes)
- a number of automotive applications are running.

The FlexRay message transmission model is based on rounds: each round consists of a constant number of slots, time intervals of the same length. A node can broadcast its messages to other nodes at statically defined slots. At most one node can do it during any slot. A high level architecture of FlexRay is presented in Figure 1.

A scheduling table of a node consists of a number of slots in which this node should be sending a frame with the corresponding identifier (identifier that is equal to the slot).

3.1 Logical components of the system

Even having small changes in the syntax might lead to a significant increase of readability and understandability of a formal language. For example, numbering the formulas allowing implicit constructs can be very helpful. To increase the readability of FOCUS\textsuperscript{ST}, we use so-called implicit else-case constructs:

- if there is no explicit mentioning of the value of an output stream for a particular transaction, then the corresponding time interval of this stream should be empty;
- if there is no explicit mentioning of the value of a variable after a particular transaction, then this variable should keep its current value.

Figure 2 presents the architecture of the FlexRay communication protocol specified in FOCUS\textsuperscript{ST}. Its assumption-part consists of three constraints:

A1: all bus configurations have disjoint scheduling tables,
A2: all bus configurations have the equal length of the communication round,
A3: Each controller can receive at most one data frame each time interval from the environment of the system.

The guarantee-part represents architecture of the FlexRay communication protocol: the system consists of the component *Cable* and *n* components *FlexRayController* (one controller component for each of *n* nodes).

The component *Cable* represents the transmission properties of a physical network cable: every received FlexRay frame has to be resent to all connected nodes, cf. Figure 3. Thus, if one of the controllers send a frame, it should be transmitted to all nodes, i.e., to all other controllers in the system. The specification has only one formula in the assumption part: it expresses that all input streams of this component have to be disjoint. This assumption is fulfilled due to the properties of the *FlexRayController* components and the overall system assumption that the scheduling tables of all nodes are disjoint (cf. assumption A2 of the *FlexRayArch* specification).

The guarantee part of this specification has also only one formula: the predicate *Broadcast* specified in Section 3.2 below.

The specification *FlexRayController* represent the controller component for a single node, cf. Figure 4. The specification does not have any assumptions on the input streams of this component, which is highlighted by *true* in the assumption part. The guarantee part represents architecture of this component, as this component is a composite one and is built from the components Scheduler and BusInterface.

Scheduler activates BusInterface according to the FlexRay schedule, cf. Figure 5: every time *t* interval, which is equal (modulo the length of the FlexRay communication cycle) to some frame identifier *i*, the frame with this identifier. The frame identifier corresponds in the scheduler table to the number of the slot in the communication round.

BusInterface (cf. Figure 6) specifies the interaction with other nodes of the FlexRay system, i.e., on what time interval what FlexRay frame...
must be send from the node, and how the sende
frames should be received. The component is
specified using by two auxiliary predicates, Send
and Receive, described in Section 3.2.

3.2 Auxiliary predicates

We define the following auxiliary predicates to
specify the FlexRay protocol: DisjointSched-
dules, IdenticCycleLength, and FrameTransmis-
sion, Broadcast, Send and Receive, cf. Figure 7.
A sheaf of channels of type Config

- fulfils the predicate DisjointSchedules, if all
  bus configurations have disjoint scheduling ta-
 bles;

- fulfils the predicate IdenticCycleLength, if all
  bus configurations have the equal length of the
  communication round.

The predicate FrameTransmission defines the
correct message transmission: if the time interval
t is equal (modulo the length of the FlexRay com-

munication round) to the element of the scheduler
table of the node k, then only the node k is al-

lowed to send data at the th time interval.

The predicate Broadcast describes properties
of FlexRay broadcast. The predicates Send and
Receive define the FOCUS relations on the streams
to represent respectively data send and data re-
ceive by FlexRay controller.

3.3 Specification of requirements

The specification FlexRayReq represents require-
ments on the protocol, cf. Figure 8: If the schedul-
ing tables are correct in terms of the predi-
cates DisjointSchedules (all bus configurations
have disjoint scheduling tables) and IdenticCycle-
Length (all bus configurations have the equal
length of the communication round), and also the
FlexRay component receives in every time in-

erval at most one message from each node (via
channels return, 1 ≤ i ≤ n), then

- the frame transmission must be correct in
the terms of the predicate FrameTransmission;

- FlexRay component sends in every time in-

erval at most one message to each node via
channels get, and store, 1 ≤ i ≤ n).

Please note that the assumption part of this spec-
ification is equal to the assumption part of the
specification FlexRayArch.

To demonstrate that the specified FlexRay
system fulfils the requirements we need to prove

\[
\text{DisjointSchedules} \\
\quad c_1, ..., c_n \in \text{Config} \\
\forall i, j \in [1..n], j \neq i : \\
\quad \forall x \in \text{rng.schedule}(c_i), y \in \text{rng.schedule}(c_j) : \\
\quad x \neq y
\]

\[
\text{IdenticCycleLength} \\
\quad c_1, ..., c_n \in \text{Config} \\
\forall i, j \in [1..n] : \\
\quad \text{cycleLength}(c_i) = \text{cycleLength}(c_j)
\]

\[
\text{FrameTransmission} \\
\quad \text{store}_1, ..., \text{store}_n, \text{return}_1, ..., \text{return}_n \in \text{Frame} = \\
\quad \text{get}_1, ..., \text{get}_n \in \text{N} = \\
\quad c_1, ..., c_n \in \text{Config} \\
\forall t \in \text{N}, k \in [1..n] : \\
\quad \text{let } s = \text{mod}(t, \text{cycleLength}(c_k)) \text{ in} \\
\quad \text{s} \in \text{schedule}(c_k) \rightarrow \\
\quad \text{get}^t_k = (s) \land \\
\quad \forall j \in [1..n], j \neq k : \text{store}^t_j = \text{return}^t_k
\]

\[
\text{Broadcast} \\
\quad \text{send}_1, ..., \text{send}_n, \text{recv} \in \text{Frame} = \\
\forall t \in \text{N} : \\
\quad \exists k \in [1..n] : \text{send}^t_k \neq \langle \rangle \rightarrow \text{recv}^t = \text{send}^t_k
\]

\[
\text{Send} \\
\quad \text{return}, \text{send} \in \text{Frame} = \text{get}, \text{activation} \in \text{N} = \\
\forall t \in \text{N} : \\
\quad \text{activation}^t \neq \langle \rangle \rightarrow \\
\quad \text{get}^t = \text{activation}^t \land \text{send}^t = \text{return}^t
\]

\[
\text{Receive} \\
\quad \text{recv}, \text{store} \in \text{Frame} = \text{activation} \in \text{N} = \\
\forall t \in \text{N} : \\
\quad \text{activation}^t = \langle \rangle \rightarrow \text{store}^t = \text{recv}^t
\]

Figure 7: Specifications of the auxiliary predicates

that the specification FlexRayArch is a refinement
of the specification FlexRayReq.
Figure 8: Specifications of the FlexRay requirements

4 RELATED WORK

4.1 FocusST

A systematic review of the Focus related approaches, incl. FocusST, as well as on the case studies they were applied on, was presented in [40]. Spatio-temporal models for formal analysis and property-based testing were presented in [1, 2] by Alzahrani et al. The authors aimed to apply property-based testing on FocusST and TLA models with temporal properties. Another approach based on FocusST, allows analysis of component dependencies [38]. This was later extended to framework for formal analysis of dependencies among services [43].

A number of case studies on the modelling of autonomous systems were presented in [44, 45, 47, 33]. There are also a number of specification and software development methodologies applying FocusST, cf. [4, 5, 3, 10, 11, 42, 48, 14, 15]. An approach introduced by Doby et al. [9] utilized Focus to provide an efficient hazard and impact analysis for automotive mechatronics systems.

4.2 FlexRay

Timing analysis of the FlexRay communication protocol were discussed in [27].

Message scheduling for the static and dynamic segments of FlexRay were analysed in [29] and [28] respectively. There are many approaches on schedule optimization of the static segment, cf. [21, 16, 53, 8, 30, 51].

A formal verification of the clock synchronization algorithm and of the bus guardian of FlexRay was conducted at INRIA [54]. In our research, we focused on the verification of the communication properties of the protocol.

Performance analysis of the FlexRay-based networks was discussed in [13, 7]. An optimization method for FlexRay network parameters was proposed in [26].

A comparison of TTP/C with FlexRay protocol was presented in [17]. A comparison of time-triggered Ethernet with FlexRay was introduced in [49]. CAN, TTCAN, FlexRay and LIN protocols in passenger vehicles were also compared in [50].

An approach for application of time-triggered paradigm (incl. the OSEKtime and FlexRay aspects) to the domain of autonomous systems [47]. An implementation of FlexRay communication controller protocol with application to a robot system was introduced in [52].

5 CONCLUSIONS

This paper presents a formal specification of the FlexRay protocol using the FocusST framework. This work extends or previous research of formal specifications of this protocol using Focus formal language and demonstrates the visual improvements as well as the simplifications of the specifications, which initial versions were presented in [31, 32].

REFERENCES

[1] N. Alzahrani, M. Spichkova, and J. O. Blech. Spatio-temporal models for formal analysis and property-based testing. In Federation of International Conferences on Software Technologies: Applications and Foundations, pages 196–206. Springer, 2016.

[2] N. Alzahrani, M. Spichkova, and J. O. Blech. From temporal models to property-based testing. In 11th International Conference on Evaluation of Novel Approaches to Software Engineering, pages 241–246. SCITEPRESS, 2017.

[3] J. Botaschanjan, M. Broy, A. Gruler, A. Harhurin, S. Knapp, L. Kof, W. Paul, and M. Spichkova. On the correctness of upper layers of automotive systems. Formal aspects of computing, 20(6):637–662, 2008.
[4] J. Botaschanjan, A. Gruler, A. Harburin, L. Kof, M. Spichkova, and D. Trachtenherz. Towards modularized verification of distributed time-triggered systems. In *Int. Symposium on Formal Methods*, pages 163–178. Springer, 2006.

[5] J. Botaschanjan, L. Kof, C. Kühnel, and M. Spichkova. Towards verified automotive software. In *ACM SIGSOFT Software Engineering Notes*, volume 30, pages 1–6. ACM, 2005.

[6] M. Broy and K. Stølen. *Specification and Development of Interactive Systems: Focus on Streams, Interfaces, and Refinement*. Springer, 2001.

[7] D. B. Chokshi and P. Bhaduri. Performance analysis of flexray-based systems using real-time calculus, revisited. In *Proceedings of the 2010 ACM Symposium on Applied Computing*, pages 351–356. ACM, 2010.

[8] S. Ding, N. Murakami, H. Tomiyama, and H. Takada. A ga-based scheduling method for flexray systems. In *Proceedings of the 5th ACM international conference on Embedded software*, pages 110–113. ACM, 2005.

[9] S. Dobi, M. Gleirscher, M. Spichkova, and P. Struss. Model-based hazard and impact analysis. *arXiv preprint arXiv:1512.02759*, 2015.

[10] M. Feilkas, A. Fleischmann, F. Hözl, C. Pfaller, K. Scheidemann, M. Spichkova, and D. Trachtenherz. A top-down methodology for the development of automotive software. *Technische Universität München*, Tech. Rep., 902, 2009.

[11] M. Feilkas, F. Hözl, C. Pfaller, S. Rittmann, B. Schätz, W. Schweizer, W. Sitou, M. Spichkova, and D. Trachtenherz. A Refined Top-Down Methodology for the Development of Automotive Software Systems – The KeylessEntry System Case Study. *Technische Universität München*, Tech. Rep., 1103, 2011.

[12] FlexRay Consortium. *FlexRay Communication System - Protocol Specification - Version 2.0*, 2004.

[13] A. Hagiescu, U. D. Bordoloi, S. Chakraborty, P. Sampath, P. V. V. Ganesan, and S. Ramesh. Performance analysis of flexray-based ecu networks. In *Design Automation Conference, 2007. DAC ’07. 44th ACM/IEEE*, pages 284–289. IEEE, 2007.

[14] F. Hözl, M. Spichkova, and D. Trachtenherz. *AutoFocus Tool Chain*. *Technische Universität München*, Tech. Rep., (TUM-I1021), 2010.

[15] F. Hözl, M. Spichkova, and D. Trachtenherz. Safety-critical system development methodology. *Technische Universität München*, Tech. Rep., (1020), 2010.

[16] M. Kang, K. Park, and B. Kim. A static message scheduling algorithm for reducing flexray network utilization. In *Industrial Electronics, 2009. ISIE 2009. IEEE International Symposium on*, pages 1287–1291. IEEE, 2009.

[17] H. Kopetz. A comparison of ttp/c and flexray. *Institut für Technische Informatik, Technische Universität Wien, Austria, Research Report*, 10:1–22, 2001.

[18] C. Kühnel and M. Spichkova. *FlexRay und FTCom: Formale Spezifikation in FOCUS*. *Technische Universität München*, Tech. Rep. I, 601:2006, 2006.

[19] C. Kühnel and M. Spichkova. Upcoming automotive standards for fault-tolerant communication: FlexRay and OSEKtime FTCom. In *EFTS 2006 International Workshop on Engineering of Fault Tolerant Systems, Universite du Luxembourg, CSC: Computer Science and Communication*, 2006.

[20] C. Kühnel and M. Spichkova. *Fault-Tolerant Communication for Distributed Embedded Systems*. In *Software Engineering and Fault Tolerance*. Software Engineering and Knowledge Engineering, 2007.

[21] M. Lukasiewycz, M. Glaß, J. Teich, and P. Milbredt. Flexray schedule optimization of the static segment. In *Proceedings of the 7th IEEE/ACM international conference on Hardware/software codesign and system synthesis*, pages 363–372. ACM, 2009.

[22] R. Makowitz and C. Temple. Flexray - a communication network for automotive control systems. In *2006 IEEE International Workshop on Factory Communication Systems*, pages 207–212, 2006.

[23] T. Nipkow, L. C. Paulson, and M. Wenzel. *Isabelle/HOL – A Proof Assistant for Higher-Order Logic*, volume 2283 of LNCS. Springer, 2002.

[24] OSEK/VDX. Fault-Tolerant Communication. Specification 1.0, 2001.

[25] OSEK/VDX. *Time-Triggered Communication. Specification 1.0*, 2001.

[26] I. Park and M. Sunwoo. Flexray network parameter optimization method for automotive applications. *IEEE Transactions on Industrial Electronics*, 58(4):1449–1459, 2011.

[27] T. Pop, P. Pop, P. Eles, Z. Peng, and A. Andreati. Timing analysis of the flexray communication protocol. *Real-time systems, 39(1-3):205–235, 2008.

[28] E. G. Schmidt and K. Schmidt. Message scheduling for the flexray protocol: The dynamic segment. *IEEE Transactions on Vehicular Technology*, 58(5):2160–2169, 2009.

[29] K. Schmidt and E. G. Schmidt. Message scheduling for the flexray protocol: The static segment. *IEEE transactions on vehicular technology*, 58(5):2170–2179, 2009.

[30] K. Schmidt and E. G. Schmidt. *Optimal message scheduling for the static segment of flexray*. In *Vehicular Technology Conference Fall (VTC*
[31] M. Spichkova. FlexRay: Verification of the FOCUS Specification in Isabelle/HOL. A Case Study. Technische Universität München, Tech. Rep., (602), 2006.

[32] M. Spichkova. Specification and Seamless Verification of Embedded Real-Time Systems: FOCUS on Isabelle. PhD thesis, TU München, 2007.

[33] M. Spichkova. Architecture: Requirements + Decomposition + Refinement. Softwaretechnik-Trends, 31:4, 2011.

[34] M. Spichkova. Human Factors of Formal Methods. In IADIS Interfaces and Human Computer Interaction. IHCI, 2012.

[35] M. Spichkova. Towards Focus on Time. In 12th International Workshop on Automated Verification of Critical Systems (AVoCS), 2012.

[36] M. Spichkova. Design of formal languages and interfaces: formal does not mean unreadable. In Emerging Research and Trends in Interactivity and the Human-Computer Interface. IGI Global, 2013.

[37] M. Spichkova. Stream Processing Components: Isabelle/HOL Formalisation and Case Studies. Archive of Formal Proofs, 2013.

[38] M. Spichkova. Formalisation and analysis of component dependencies. Archive of Formal Proofs, 2014.

[39] M. Spichkova. Spatio-temporal features of Focus. arXiv preprint arXiv:1610.07884, 2016.

[40] M. Spichkova. (Auto) Focus approaches and their applications: A systematic review. arXiv preprint arXiv:1711.08123, 2017.

[41] M. Spichkova, J. Blech, P. Herrmann, and H. Schmidt. Modeling spatial aspects of safety-critical systems with Focus. In Mod-eVVA2014, pages 49–58. CEUR, 2014.

[42] M. Spichkova and A. Campetelli. Towards system development methodologies: From software to cyber-physical domain. In First International Workshop on Formal Techniques for Safety-Critical Systems (FTSCS’12), 2012.

[43] M. Spichkova and H. Schmidt. Towards logical architecture and formal analysis of dependencies between services. In The 2014 Asia-Pacífic Services Computing Conference, 2014.

[44] M. Spichkova and M. Simic. Towards formal modelling of autonomous systems. In Intelligent Interactive Multimedia Systems and Services, pages 279–288. Springer, 2015.

[45] M. Spichkova and M. Simic. Autonomous systems research embedded in teaching. In Intelligent Interactive Multimedia Systems and Services, pages 268–277. Springer, 2017.

[46] M. Spichkova and M. Simic. Human-centred analysis of the dependencies within sets of proofs. In Knowledge-Based and Intelligent Information & Engineering Systems, pages 2290–2298. Elsevier, 2017.

[47] M. Spichkova, M. Simic, and H. Schmidt. From automotive to autonomous: Time-triggered operating systems. In Intelligent Interactive Multimedia Systems and Services 2016, pages 347–359. Springer, 2016.

[48] M. Spichkova, X. Zhu, and D. Mou. Do we really need to write documentation for a system? In International Conference on Model-Driven Engineering and Software Development (MODELSWARD’13), 2013.

[49] T. Steinbach, F. Korf, and T. C. Schmidt. Comparing time-triggered ethernet with flexray: An evaluation of competing approaches to real-time for in-vehicle networks. In Factory Communication Systems (WFCS), 2010 8th IEEE International Workshop on, pages 199–202. IEEE, 2010.

[50] S. C. Talbot and S. Ren. Comparison of fieldbus systems can, ttcan, flexray and lin in passenger vehicles. In Distributed Computing Systems Workshops, 2009. ICDCS Workshops’ 09. 29th IEEE International Conference on, pages 26–31. IEEE, 2009.